



Performance assessment & synergic operation of algorithmic solutions enabling opportunistic networks– D4.2

Project Number:	ICT-2009-257385
Project Title:	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet - OneFIT
Document Type:	Deliverable

Contractual Date of Delivery:	30.06.2012
Actual Date of Delivery:	30.06.2012
Editors:	J. Pérez-Romero (UPC)
Participants:	Please see the list of contributors
Workpackage:	WP4
Estimated Person Months:	
Nature:	PU ¹
Version:	1.0
Total Number of Pages:	209
File:	OneFIT_D4.2_20120630.docx

Abstract

This deliverable describes in detail the algorithmic solutions for enabling opportunistic networks. Each algorithm is accompanied by performance evaluations, according to proper KPIs in representative scenarios. Performance assessments also include aspects related to the practicality of the solutions proposed. Finally, considerations and steps taken for the integration and synergic operation among the different algorithms will be discussed in the report.

Keywords List

Opportunistic networks, algorithms, infrastructure-less networks, traffic aggregation, suitability determination, route selection, node selection, spectrum selection.

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PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Executive Summary

This document presents the detailed descriptions of the algorithmic solutions for enabling opportunistic networks developed in the OneFIT project [1].

The first part of the document describes the different algorithms that have been proposed to cope with the technical challenges arising in the ON management stages, including the problem formulation, the algorithm specification and the integration with the OneFIT architecture and C4MS signalling aspects. Proposed algorithms include the ON suitability determination in different scenarios, the spectrum opportunity identification and selection, the nodes and routes selection, and the capacity extension through femtocells. The second part of the document presents the performance evaluation of each of the specified algorithms, according to proper Key Performance Indicators in representative scenarios, and including aspects related to the practicality of the different proposed solutions. In the following, a list is presented with the main conclusions that are obtained for each of the considered main topics:

- **ON Suitability determination:** The probability of direct communication between devices to establish the ON has been evaluated in the “infrastructure supported device-to-device communication” and “coverage extension” scenarios. It is obtained that this probability depends on the probability of the users being in the same “Area of Interest” and on the range of the wireless interface.
- **Spectrum opportunity identification and selection:** Different approaches are proposed depending on the specific scenario considerations. The fittingness factor concept has been proposed as a novel metric that captures the time-varying suitability of available spectrum resources to different applications supported in each ON link. Advanced statistics of this metric capturing the dynamic radio environment are stored in a Knowledge Database and used to support the spectrum selection and spectrum mobility algorithms. Performance evaluation shows that the strategy introduces significant gains with respect to a random selection and performs very closely to an upper-bound optimal scheme. The possibility of jointly considering the frequency, bandwidth and radio access technique selection has also been studied. In particular, a modular decision flow approach is presented demonstrating how the algorithm can adequately select the band depending on the transmission range for guaranteeing a proper QoS to the users. The inclusion of machine learning in the knowledge acquisition on spectrum usage is also addressed in this document. In particular, a novel channel identification algorithm is presented targeted at modelling the spectrum occupancy and identification of spectrum pools for opportunistic access by secondary network. Results reveal the capability of learning by means of successful interactions with the environment (rather than relying on spectrum usage history) which resources to be used in order to avoid/not cause harmful interference as well as providing a suitable Quality of Service (QoS). Finally, another field of study in this area is the inclusion of the spectrum aggregation in the spectrum selection. An algorithm is proposed based on a utility function that considers the total throughput, the number of channel switching, and the number of bands for aggregate channels, with a Q-learning approach to determine the optimal weights.
- **Node and route selection:** Different strategies have been proposed and analysed regarding the capability to select the adequate nodes to form the ON and the most suitable routes between them. First, an algorithm on knowledge-based suitability determination and selection of nodes and routes is proposed for the capacity extension scenario in which a congestion situation occurs in the infrastructure. In this case, the route selection is based on the Ford-Fulkerson maximum flow algorithm while the node selection is based on a fitness function that weights different parameters of the candidate nodes. Evaluation reveals the impacts in terms of transmission power of the involved terminals and base stations, in terms of the quality of the communication in terms of delay and in terms of the existing load. In

another approach, a network coding optimization is proposed for multi-flow route co-determination, based on the introduction of delegated nodes. Results show good improvements on the throughputs in terms of number of data packets to be exchanged between pair nodes. The inclusion of QoS and spectrum-awareness considerations in the routing is also evaluated, proposing a routing protocol that makes an opportunistic use of the available channels. Another work in this area addresses the creation and maintenance of network topology through enabling coordination in decision making among nodes taking into account different parameters to establish links/topology with a set of desired global properties and constraints. Results indicate that the proposed models can provide practical yet optimal power levels to minimize the power utilization while maintaining connectivity. The establishment of a WLAN network between different devices using the connections allowed by another technology is considered in the so-called UE-to-UE trusted direct path activity. It deals with the selection of the candidate access point and the operating channel to fulfil the QoS and power minimization requirements. Focusing specifically on the scenario "Opportunistic resource aggregation in the backhaul network", a first approach proposes an application cognitive multi-path routing algorithm for wireless mesh networks that selects and establishes the appropriate multiple paths to support aggregation of the backhaul resources. This allows increasing the overall capacity of the network turning into drastic improvements in the QoS levels. Also in the same scenario an algorithm is proposed that, based on contextual data gathered from the environment and end users, performs the node selection for multimedia content placement and distribution taking into account request distribution, popularity of multimedia content, status of caching storage of WMN nodes and user's behaviour. The evaluation reveals the advantages and robustness of the proposed approach that allow cost savings for the content provider while keeping the same QoS.

- Capacity extension through femtocells: A novel algorithm is presented addressing optimization problem of allocation of network resources to reroute macro-terminals to the femtocells while keeping the minimum transmit power levels and in this way extending the capacity of the congested networks. The problem is mathematically formulated and solved by means of a novel greedy algorithm. Results reveal that the proposed algorithm outperforms both Simulated Annealing and Tabu Search reference algorithms in terms of solution quality and runtime. In addition, the benefits that derived from the use of femtocells at the energy consumption of a macro BS and the battery lifetime of terminals are studied.

Finally, the last part of the deliverable deals with the steps taken for the integration and synergic operation among algorithms, with a particular focus on the comprehensive solutions for the technical challenges of spectrum opportunity identification and selection and node and route selection, identified as two of the major blocks to cope with the ON management stages. More specifically, the solution for spectrum opportunity identification and selection is based on the interaction between a decision making entity and a knowledge management functional block which use the information captured from the radio environment, categorized in terms of context awareness, operator policies and user/application profiles. An evaluation of the different elements of the framework is presented to consolidate the importance of the different specificities brought by the different solutions. Similarly, for the route and node selection, the proposed solution considers that decisions are conducted both locally and in a centralized manner. Performance evaluation of this approach presents the benefits brought in terms of energy consumption in both the infrastructure and the terminals, as well as in terms of load, delay and resource utilization.

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Table of Acronyms

Acronym	Meaning
3GPP	Third Generation Partnership Project
ADTL	Average Delivery Tree Length
AOI	Area of Interest
AP	Access Point
ARCF	All Replica Containing File
BS	Base Station
BW	BandWidth
BWRC	Best among the Worst Residual Capacities
C4MS	Control Channels for the Cooperation of the Cognitive Management Systems
CA	Context Awareness
CA	Channel Allocation
CBR	Constant Bit Rate
CDN	Content Delivery Network
CMON	Cognitive Management system for the Opportunistic Network
CR	Cognitive Radio
CSCI	Cognitive management System for the Coordination of the Infrastructure
D2D	Device-To-Device
DM	Decision Making
DRA	Dynamic Resource Allocation
DSM	Dynamic Spectrum Management
DSOONPM	Dynamic Self-Organizing Network Planning and Management
DTN	Delay Tolerant Network
DYMO	Dynamic Manet On-Demand Routing
eNB	evolved Node B
eHNB	evolved Home NodeB
E-SMLC	Evolved-Serving Mobile Location Center
ETX	Expected Transmission Count
FC	FemtoCell

FSA	Fixed Spectrum Assignment
GDC	Gradual Deployment of Carriers
GW	GateWay
HMM	Hidden Markov Model
IMT	International Mobile Telecommunications
ISM	Industrial, Scientific and Medical
JADE	Java Agent Development Platform
JRRM	Joint Radio Resource Management
KD	Knowledge Database
KM	Knowledge Manager
KPI	Key Performance Indicator
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MANET	Mobile Ad-Hoc Network
MID	Multiple Interface Declaration
MIH	Media Independent Handover
MILP	Mixed Integer Linear Program
ML	Maximum Likelihood
MME	Mobility Management Entity
MPR	Multi Point Relay
MTLS	Monitoring → Triggering → Learning → Selection
OF	Objective Function
OFDMA	Orthogonal Frequency Division Multiple Access
OLSR	Optimized Link State Routing
ON	Opportunistic Network
ONE	Opportunistic Network Environment
OPA	Operator Policy Acquisition
P2P	Peer To Peer
PM	Profile Management
PU	Primary User

QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
REM	Radio Environment Map
RL	Reinforcement Learning
RRM	Radio Resource Management
RTSP	Real Time Streaming Protocol
SA	Spectrum Aggregation
SA	Simulated Annealing
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference and Noise Ratio
SM	Spectrum Mobility
SMS	Short Message Service
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SpHO	Spectrum HandOver
SS	Spectrum Selection
STA	STAtion
SU	Secondary User
TC	Topology Control
TD	Time Difference
TS	Tabu Search
TV	TeleVision
UDP	User Datagram Protocol
UE	User Equipment
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network

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1. Introduction

This deliverable describes in detail the algorithmic solutions for enabling opportunistic networks developed in the OneFIT project [1]. Each algorithm will be accompanied by performance evaluations, according to proper KPIs in representative scenarios. Performance assessment will also include aspects related to the practicality of the proposed solutions. Finally, considerations and steps taken for the integration and synergic operation among the different algorithms will be discussed in the report.

The deliverable is organized in three main chapters. Chapter 2 describes the different algorithms that have been developed to cope with the technical challenges arising in the ON management stages. For the different algorithms, the problem is formulated and the algorithm is specified, point out also the integration with the OneFIT architecture presented in deliverable [3]. The considered algorithms address first the ON suitability determination in different scenarios. Then the chapter focuses on the spectrum opportunity identification and selection technical challenge, for which different approaches are presented. Next the node and route selection challenge is addressed, including also different strategies that consider specific problems within this technical challenge. Finally, specific solutions are presented to the capacity extension problem by means of femto-cells and to the macro-to-femto offloading mechanism.

Chapter 3 presents the performance evaluation of each of the specified algorithms. The chapter starts with the general aspects of the evaluation methodology that has been followed, by means of simulations. Then, for each algorithm the evaluation planning is presented, including the relevant metrics considered in the evaluation, the benchmark references, and the details about the evaluation platform and model. This is followed by the performance evaluation results achieved by each strategy.

The steps taken for the integration and synergic operation among algorithms are addressed in chapter 4. It discusses first the general approach that has been followed in OneFIT WP4. It consists in a first analysis to identify the interactions and synergies between algorithms, leading to the identification of two major blocks, dealing with spectrum opportunity identification and selection and with node and route selection, respectively. Based on this identification, subsequent chapters present the comprehensive OneFIT solutions for these two blocks, reflecting the work carried out up to the deliverable's date in Task 4.3.

2. Algorithmic Solutions

2.1 Suitability determination for direct device-to-device (D2D) communication

2.1.1 Problem formulation and algorithm concept

This section describes an algorithm for the suitability determination of the OneFIT scenario 3 on Infrastructure supported device-to-device (D2D) communication [3].

In today's networks, the user traffic is usually sent from a first terminal to the infrastructure network where it is then routed towards the destination. However, in certain situations it can be beneficial to use a direct (D2D) link for the communication as described in the OneFIT scenario 3 on infrastructure supported device-to-device communication [3] and as shown in Figure 1. With such a solution, the traffic can be offloaded from the infrastructure network towards the D2D link.

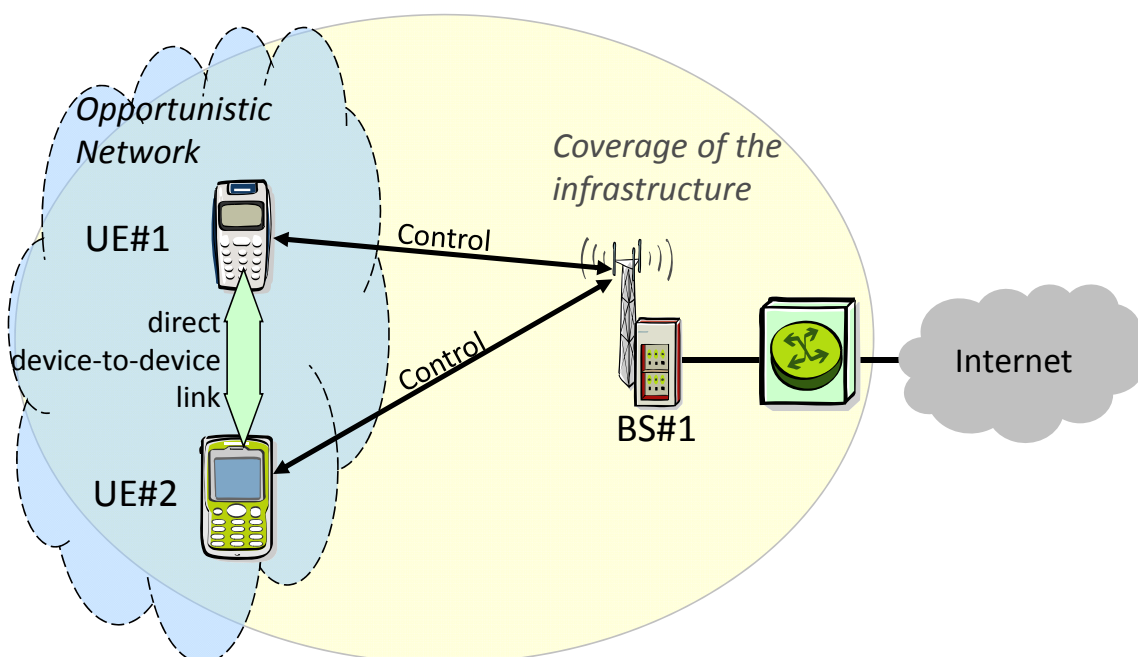


Figure 1: Infrastructure supported opportunistic networking via direct device-to-device communication

Figure 2 shows the Flow-chart of the principle procedure to be executed on infrastructure side to determine if a direct device-to-device link is feasible. If a connection setup request is received different decisions must be made. First, policies must be checked if opportunistic networking is allowed and the service requirements must be checked if the service can benefit from an opportunistic network. For example, for a video conference, the users can benefit from a possibly good performance of the direct D2D link and the infrastructure network benefits from the traffic offloading. For other services, e.g. the exchange of an SMS, an ON shall not be created because the overhead for establishing an ON would be much higher than any savings for the traffic offloading.

In the next steps, it is checked whether both endpoints are attached to the same network, whether both endpoints support direct device-to-device links and whether the two endpoints are in geographical neighborhood. If these conditions are met, then the direct link is seen as feasible and a discovery process shall be started. If the devices discover each other with sufficient quality, then an ON shall be created, else the ON is not feasible.

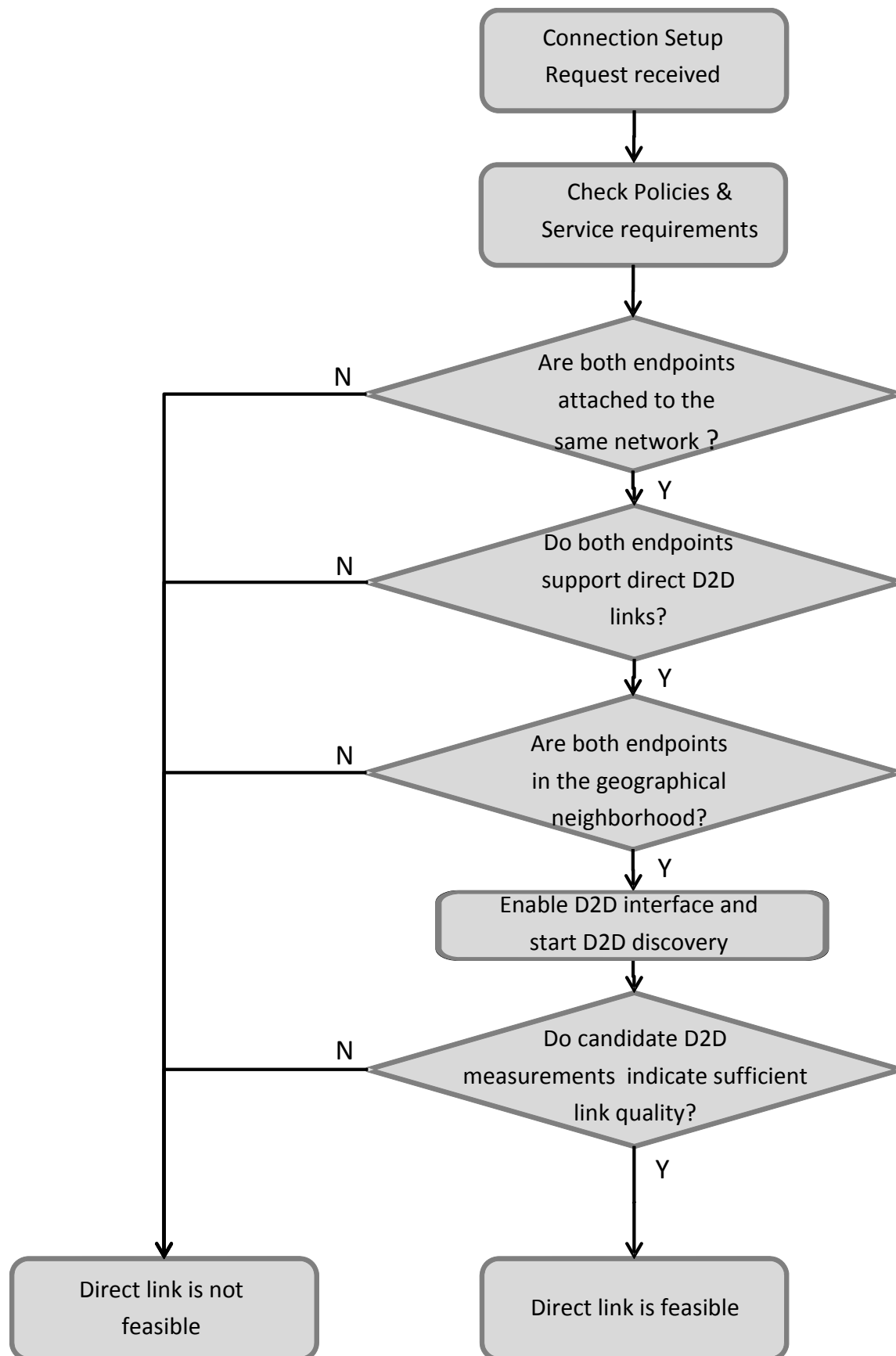


Figure 2: Suitability Determination for an Infrastructure supported direct device-to-device communication

2.2 Suitability determination for the coverage extension scenario

2.2.1 Problem formulation and algorithm concept

This section describes an algorithm for a scenario where a UE is first inside the coverage of an infrastructure network but is then moving outside the coverage. This scenario is shown in Figure 3 and described in more detail as scenario 1 “opportunistic coverage extension” in [3].

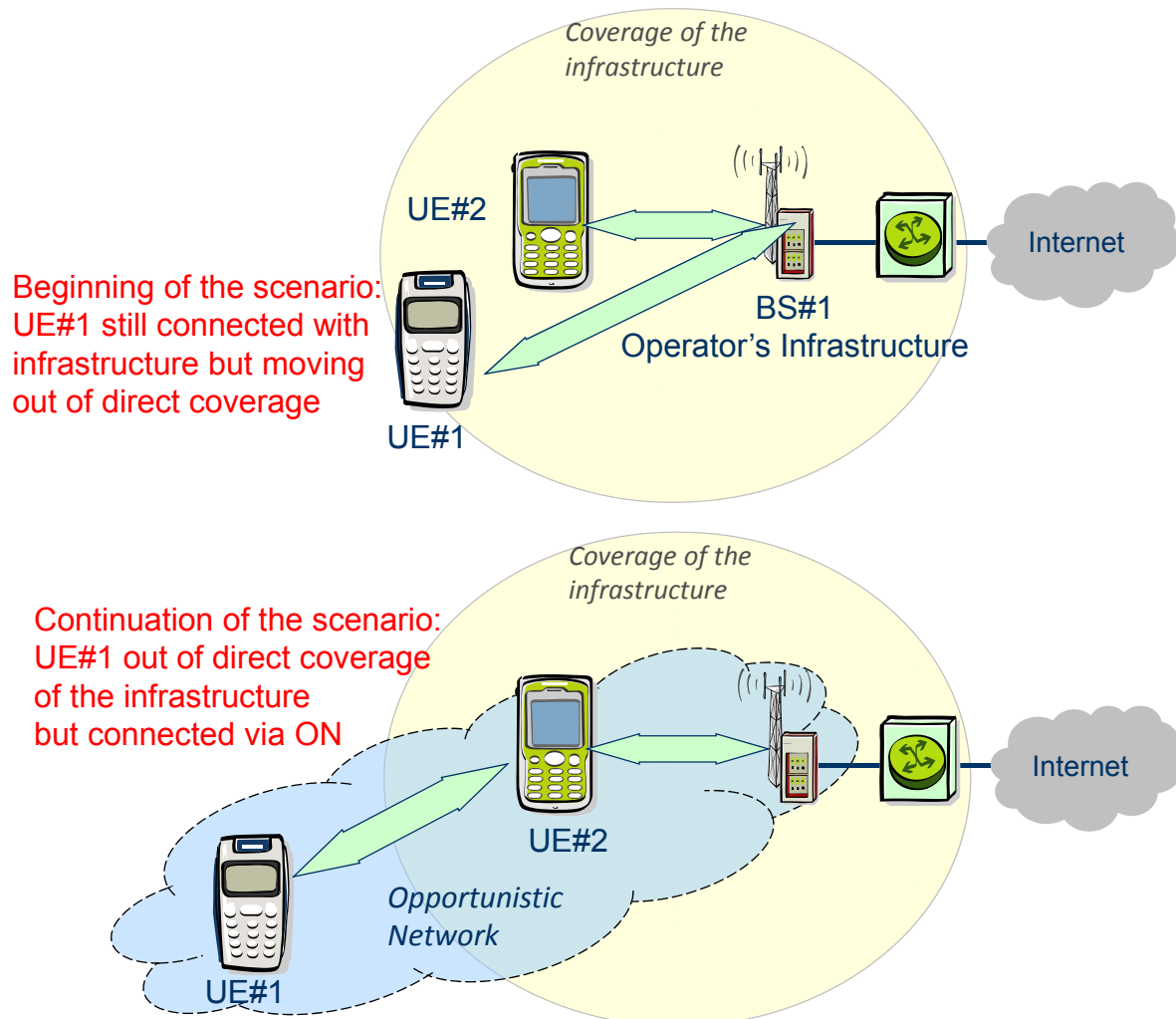


Figure 3: Opportunistic coverage extension when a UE is going out of infrastructure coverage

Figure 4 shows the flow-chart for the procedure to be executed on infrastructure side when a device is going out of infrastructure coverage. When a terminal is moving out of the infrastructure coverage, the radio conditions are getting worse. If certain threshold are crossed (e.g. link quality or signal strength going below a threshold), then the Radio Resource Management (RRM) is informed about this event. As with traditional RRM procedures, it is checked if a handover to another cell of the infrastructure is possible. If so, then the handover will be executed.

If such a handover to another cell is not possible, then the suitability determination to find a supporting device for an ON creation will be started. The algorithm searches through the list of devices attached to the current cell or neighbour cells for at least one device in the geographical neighbourhood which supports opportunistic networking and which has the capabilities to provide a direct D2D link to the terminal going out of coverage.

If such a supporting device is found, then the radio interface for the D2D link is activated (if not already active) and discovery procedures to detect the other device are initiated. If the devices discover each other and the direct link is estimated to provide sufficient quality, then an ON can be created to provide coverage extension. If the devices do not discover each other or the link cannot be established, then a search for another supporting device in the neighbourhood shall be initiated and the procedure shall be repeated until a coverage extension can be provided or a decision is made that a coverage extension cannot be provided.

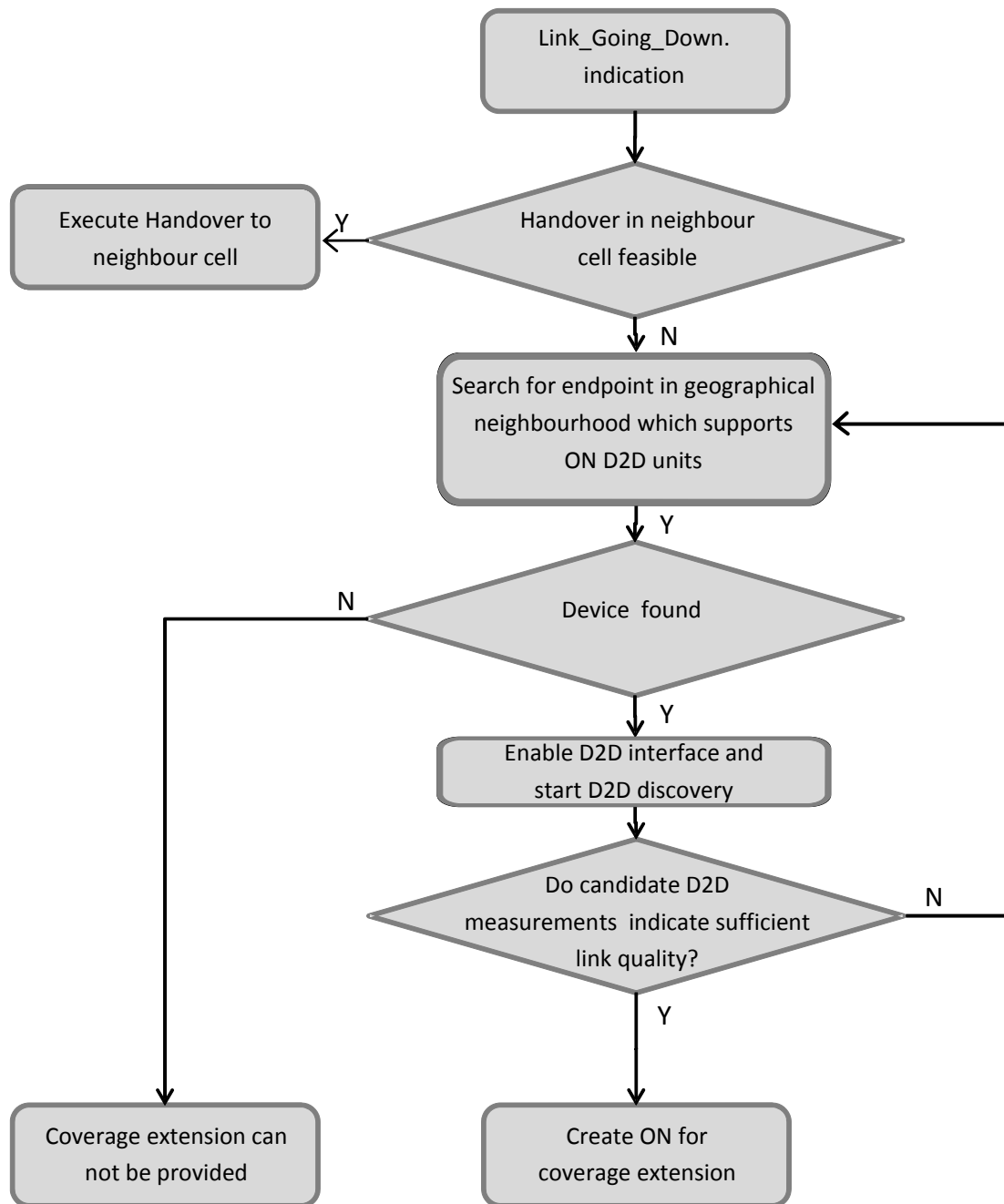


Figure 4: Suitability Determination for the coverage extension scenario

2.3 Modular decision flow approach for selecting frequency, bandwidth and radio access technique for ONs

2.3.1 Problem formulation and algorithm concept

In this section spectrum allocation problem is considered jointly with network interface selection. Situations where operator governed ad hoc network is required or there exists a node which is out of BS coverage area are considered. These kinds of problems can be solved by establishing short range links between UEs to route traffic through UEs to BS. Modular decision flow approach is used to find and allocate suitable spectrum, RAT and BW for each short range link in ON. Algorithm selects the used parameters to mitigate the interference toward other users in operator network at the same time ensuring its own transmission success and fairness of the whole ON. One of the main objectives is to ensure adequate QoS for users with different traffic type taking into account applications delay or throughput sensitivity.

Algorithm is suitable for opportunistic coverage extension and infrastructure governed opportunistic ad hoc network scenarios. With slight modifications algorithm can be considered for all scenarios put our focus will be on these two scenarios.

During ON Lifecycle algorithm is executed on suitability determination, creation, and maintenance phases. In suitability determination phase the algorithm detects the potential radio paths and RATs. In creation phase algorithm selects RAT, bandwidth, and spectrum for ON. In maintenance phase the algorithm can be used to assign new RAT, bandwidth and spectrum for ON.

2.3.2 Algorithm specification

The algorithm selects and allocates spectrum, bandwidth and RAT for one or several ON short range link. It can be used for coverage extension or operator governed ad hoc network creation and with minor changes algorithm is suitable for all scenarios to allocate spectrum, bandwidth and RAT where short range links are needed.

In simplest case algorithm needs to allocate resources only for one link between nodes i and j . Let $A_{i,j}^{node}$ denote set of bands supported by both nodes $i \in N$ and $j \in N$, where N is set of nodes selected or candidates for ON. Similarly $R_{i,j}$ is set of RATs supported by node i and j . ISM (Industrial, Scientific and Medical) including 60 GHz band, TV, and IMT (International Mobile Telecommunications) bands are considered in this studies. For RATs possible alternatives are WLAN, LTE, and LTE-A. Each RAT supports several bandwidths thus W_r is used to denote set of bandwidths supported by RAT $r \in R_{i,j}$.

A^{policy} is set of bands supported by policy and this is the same for whole network within same geographical area. $A^{policy} \cap A_{i,j}^{node}$ is set of bands available for ON link between nodes i and j . Let $Q_{i,j}$ denote a set of all possible three parameters combinations $[b, w, r]$ for link between nodes i and j . Three parameters combinations are formed using $\forall r \in R_{i,j}, \forall w \in W_r, \forall b \in A^{policy} \cap A_{i,j}^{node}$.

We make assumption for each RAT of their maximum mobility level to support certain data rates. Maximum velocity supported by RAT r , and bandwidth w is $v_{r,w}$. Velocity of node i is v_i . If $v_{r,w} > v_i$ then combination $[b, w, r]$ is maintained in set $Q_{i,j}$. Otherwise combination $[b, w, r]$ is discarded.

Friis equation is used to calculate required transmission power $p_{t,b,w,r}$ for $[b, w, r]$. $p_{t,b,w,r}$ is transmission power for band b , RAT r , and bandwidth w . $p_{t,b}$ is maximum allowed transmission power in band b . Required transmission power has to be below transmission power constraint in band b $p_{t,b} > p_{t,b,w,r}$. Combination which satisfy this requirement are kept in set $Q_{i,j}$. All the remaining combinations in this stage are suitable to be allocated for ON and they are sorted in ascending priority order using following objective function, which maximizes the requirements,

$$[b, w, r] = \arg \max_{B, W, R} \omega_1 T(w, r) + \omega_2 S(b) + \omega_3 O(r, b) \quad (1)$$

where T is normalized bitrate in bits per second for RAT r and bandwidth w . S is spectrum occupancy level of band b which purpose is to balance load among bands. O is operator satisfaction level for RAT r and band b . The satisfaction level is defined so that 60 GHz band is considered most favourable and operator own band least favourable so that operator own band is used as rarely as possibly for ON. Respectively WLAN is favoured over other RATs. $\omega_1, \omega_2, \omega_3$ are weights which depend on used application sensitivity to throughput as well as used scenario.

After the spectrum band is selected, its availability needs to be examined. There are different methods to obtain knowledge about the spectrum availability including e.g. control channels, databases and spectrum sensing techniques. The different methods have different capabilities and requirements and the method to be used depends on the selected band, see [4]. If band of combination is IMT band, i.e. operator own band, its availability is known by the operator and the operator can use its internal control channels to retrieve information about the current status of spectrum use and allocate free resources to the ON. If band is either TV or ISM band, spectrum availability has to be checked using control channels, databases, spectrum sensing techniques or combinations thereof. More detailed description of the selection of methods to obtain knowledge about spectrum availability and spectrum sensing technique selection can be found in [4] and [5]. If spectrum is available combination can be allocated for ON. Otherwise first combination is discarded and combination in second highest priority selected and its availability is examined. This is continued until suitable combination can be found. Figure 5 represents the proposed decision flow approach.

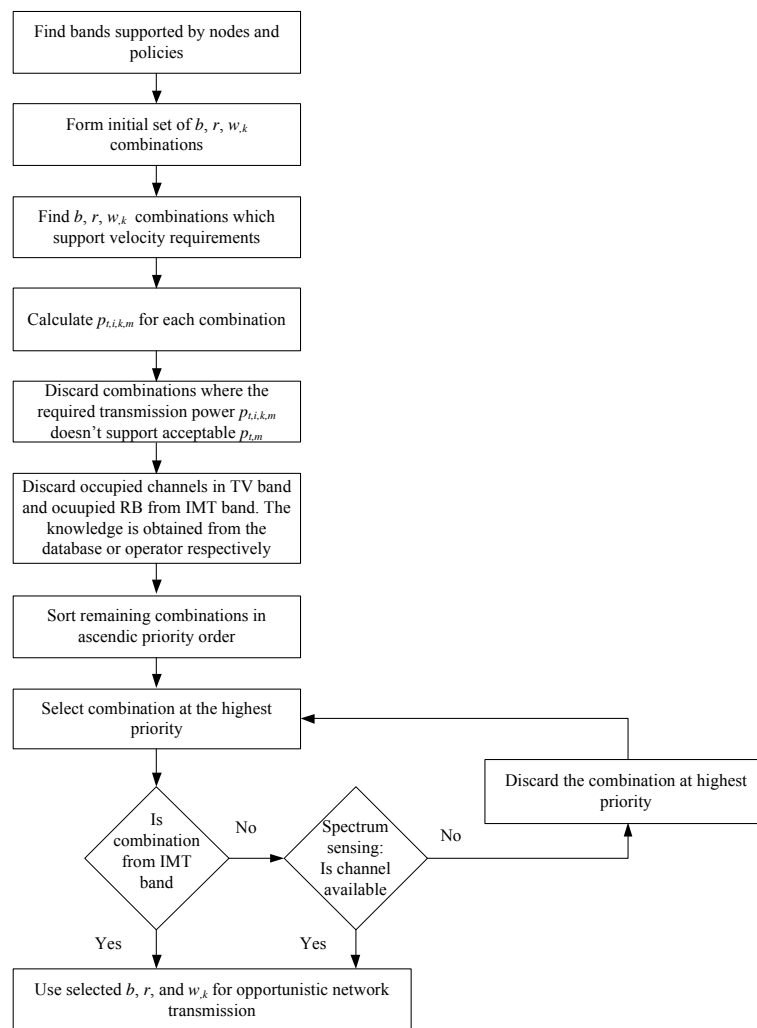


Figure 5: Modular decision flow approach

2.3.2.1 Algorithm inputs and outputs

Input parameters used in modular decision flow approach are:

- Policy information about spectrum bands
- Policy information about techniques for channel availability check
 - Requirement for detection probability, available time, available a priori information, and operational signal-to-noise ratio (SNR).
- Mobile terminal velocity
- Policy information about acceptable transmission power levels
- Sensing information about channel availability
- Database information about channel availability
- Node capabilities: indication of spectrum sensing capability, supported RATs and frequency bands
- Application requirements: data type and minimum required bit rate

Output parameters are:

- Selected band, bandwidth and RAT for ON

2.3.3 Integration in OneFIT architecture

Figure 6 shows how algorithm is mapped onto OneFIT functional architecture. The decision on used spectrum, bandwidth and RAT is done in CMON side in decision making block where the output parameters are sent to corresponding nodes to form link between ON nodes. Figure 7 illustrates the C4MS messages needed to be exchanged during ON creation phase when running modular decision flow.

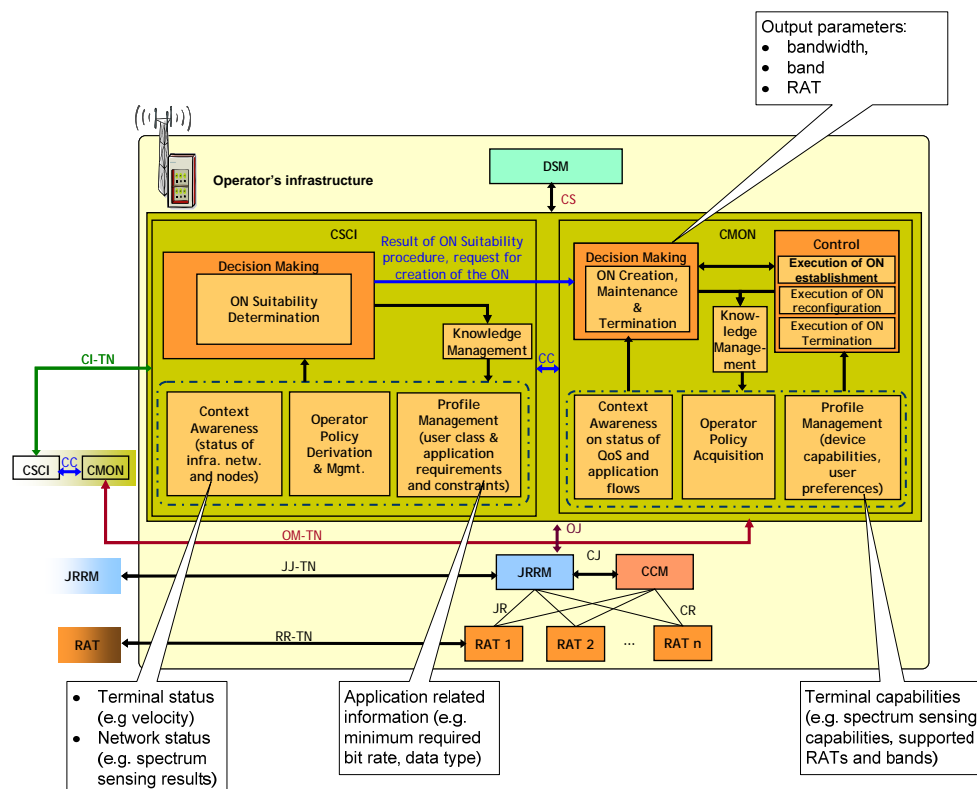


Figure 6: Mapping of Modular decision flow approach to OneFIT functional architecture

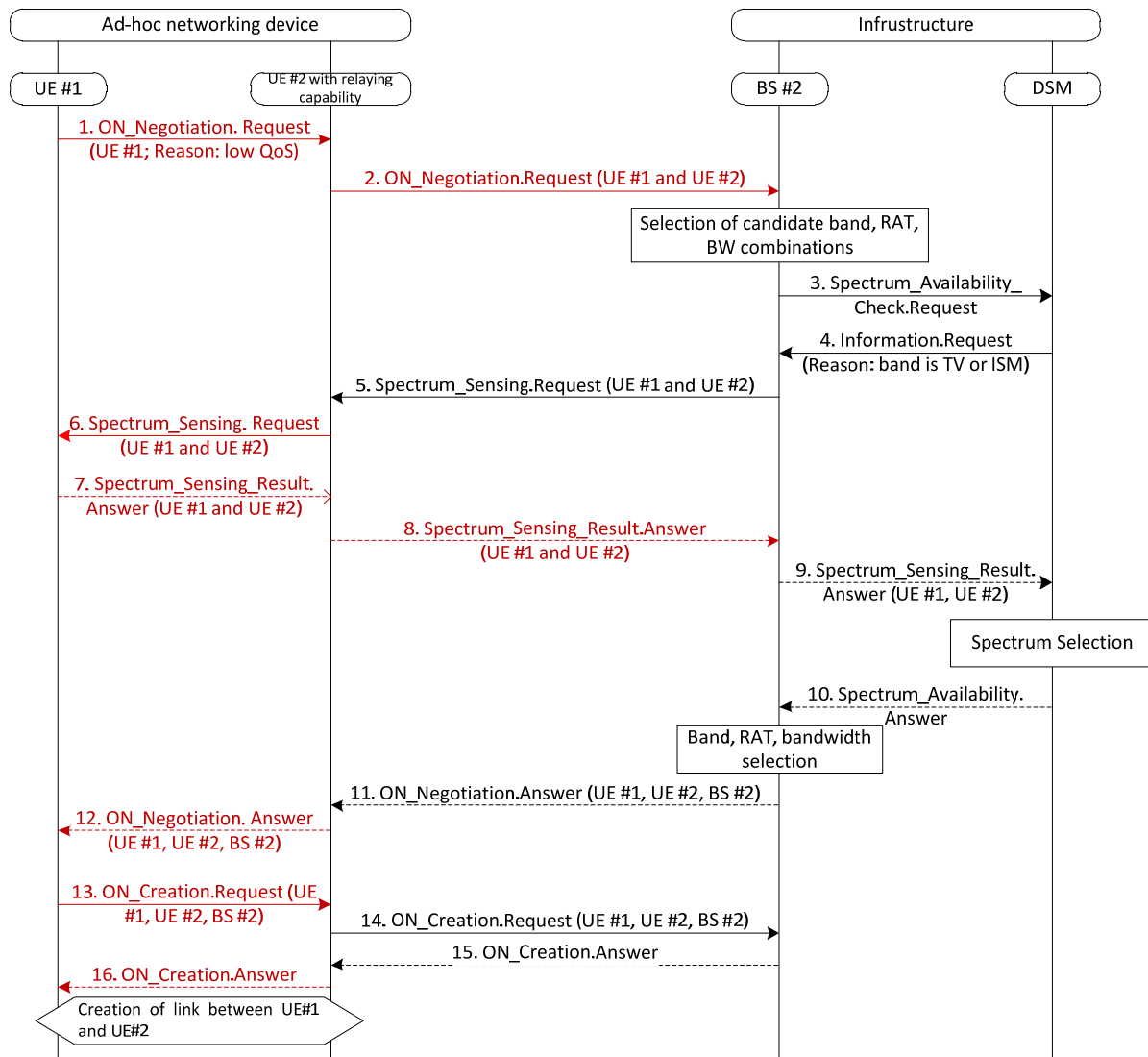


Figure 7: Message Sequence Chart for Modular Decision Flow Approach in ON Creation Phase

2.4 Fittingness factor-based spectrum selection

2.4.1 Problem formulation and algorithm concept

The problem considered here is the selection of the spectrum to be assigned to a set of radio links between pairs of terminals and/or infrastructure nodes. Each radio link belongs to one ON, and one ON can be composed of one or several radio links. The purpose of each radio link is to support a certain CR application with certain bit rate requirements.

The algorithm uses as input the set of available spectrum blocks (referred here as pools) resulting from the spectrum opportunity identification, together with the characteristics of each pool in terms of available bit rate based on radio considerations.

The algorithm makes use of the fittingness factor concept as a metric to capture how suitable a specific spectrum pool is for a specific radio link. Different statistics regarding the observed fittingness factor based on the accumulated experience are stored and used to make decisions. The spectrum selection is done either when a new application needs to be established or as a result of changes in the radio conditions or in the current active links.

The technical challenge of spectrum opportunity identification and spectrum selection is relevant to all the use cases identified in the scenarios of D2.1 [2], in which a spectrum needs to be selected to set-up the different links of an opportunistic network.

Within the ON lifecycle, the spectrum selection problem considered here is applicable in the following stages:

- ON creation: In this case the algorithm is executed whenever a new link has to be established in an ON and for that purpose an adequate spectrum pool has to be assigned.
- ON maintenance stage: In this case, the algorithm is executed whenever some changes in the radio environment have been detected such as modifications in the radio and interference conditions of a certain link, or a link release (meaning that we can reallocate the spectrum that was used by the released link to another link). As a result of the spectrum selection during ON maintenance, it is possible that spectrum handover procedures are triggered, whenever the spectrum allocated to any of the active links is modified.

2.4.2 Algorithm specification

2.4.2.1 Fittingness factor definition

Let us consider a set of L different radio links that need to be established between pairs of terminals and/or infrastructure nodes. The purpose of each radio link is to support a certain application. The l -th application is characterized in terms of a required bit-rate $R_{req,l}$ and a duration $T_{req,l}$. The available spectrum is modelled as a set of P spectrum pools each of bandwidth BW_p . Based on radio link requirements and spectrum pool characteristics, the general aim is to efficiently assign a suitable spectrum pool for each of the L radio links.

In order to assess the suitability of spectral resources to support heterogeneous services, the so-called "Fittingness Factor" ($F_{l,p}$) is proposed as a metric capturing how suitable each p -th spectrum pool is for each l -th radio link/application. $F_{l,p}$ will particularly assess the suitability in terms of the bit rate that can be achieved operating in the spectrum pool p (denoted as $R(l,p)$) versus the bit rate required by the application l ($R_{req,l}$).

From a general perspective, the fittingness factor can be formulated as a function of the utility $U_{l,p}$ the l -th link can obtain from the p -th pool, where the utility is defined as[6]:

$$U_{l,p} = \frac{(R(l,p) / R_{req,l})^{\xi}}{1 + (R(l,p) / R_{req,l})^{\xi}} \quad (2)$$

where ξ is a shaping parameter that allows the function to capture different degrees of elasticity of the application with respect to the required bit rate. The achievable bit-rate by link l using pool p ($R(l,p)$) will depend on the radio and interference conditions existing in pool p .

Based on the above concept, the fittingness factor is defined as:

$$F_{l,p} = \frac{1 - e^{-K \times U_{l,p} / (R(l,p) / R_{req,l})}}{\lambda} \quad (3)$$

where K is a shaping parameter and λ is a normalization factor to ensure that the maximum of the fittingness factor is equal to 1, given by:

$$\lambda = 1 - e^{-\frac{K}{(\xi-1)^{1/\xi} + (\xi-1)^{(1-\xi)/\xi}}} \quad (4)$$

The proposed function increases with $R(l,p)$ up to the maximum at $R(l,p) = \sqrt[\xi]{\xi-1} \times R_{req,l}$. This means that $F_{l,p}$ decreases for $R(l,p) \gg R_{req,l}$ which targets an efficient usage of spectral resources by reducing

the value of the fittingness factor whenever the available bit rate is much higher than the required one.

2.4.2.2 Algorithm inputs and outputs

The list of inputs used by the proposed algorithm to perform the spectrum selection is the following:

- List of available spectrum pools (*Av_pools*): This information is provided by the DSM as a result of the spectrum opportunity identification. Each spectrum pool k is characterized by:
 - Central frequency f_k
 - Bandwidth: BW_k
- Bit rate requirement of the link l to be assigned: $R_{req,l}$
- Duration of the application to be supported by link l : $T_{req,l}$
- Current_Assignment: List of assignments $\{l,p\}$ of spectrum pools p to currently active links l .
- Allocated_pools: List of spectrum pools that have already been allocated to other links. This information is kept by the spectrum selection function.
- Fittingness factor statistics database: This database is maintained by the algorithm, based on measurements of link context information when the different links utilise the available blocks. In addition to the last measured value of fittingness factor $F_{l,p}$ a number of statistics are stored. They will be detailed in section 2.4.2.4, especially devoted to the knowledge database.

The algorithm output will be the assignment of pools to active links.

2.4.2.3 Algorithm operation and functional entities

In order to perform the assignment of pools to links, the algorithm operation is based on the following functional entities (see Figure 8):

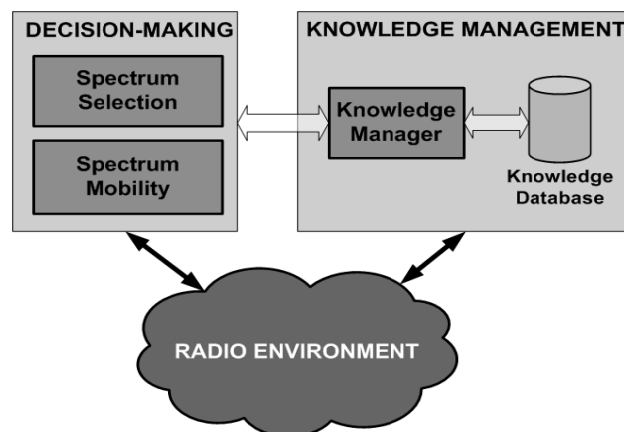


Figure 8: Functional architecture of the proposed Fittingness Factor-based Spectrum Management Framework

- The Knowledge Management entity, which is responsible for storing and managing the relevant knowledge obtained from the radio environment to be used in the decisions made by the Decision-Making entity. It is materialized by a KnowledgeManager(KM) that monitors the suitability of existing spectral resources to support heterogeneous services based on information retrieved from a Knowledge Database (KD).
- The Decision-Making entity, which is responsible for assigning the appropriate pools to the different links. For that purpose, it interacts with the KM that will provide the relevant

information for the decisions to be made. Decision-making is split into two functional entities: Spectrum Selection (SS), which will pick up a suitable pool for each communication whenever a new service request arrives, and Spectrum Mobility (SM), which will perform the reconfiguration of assigned pools whenever changes occur in the environment and better pools can be found for some services.

Both entities will be detailed in the following sub-sections.

2.4.2.4 Knowledge Management

a) Knowledge Database

In order to enable a global characterization of the suitability of a given pool p to a given link l based on the past history when using this pool, KD will retain some statistics of $F_{l,p}$. The database will be fed by measurements extracted from the radio environment in terms of $R(l,p)$ for active link/pool pairs. Then, $F_{l,p}$ will be computed following (3) and will be stored in the database together with the corresponding time stamp.

Considering that $F_{l,p}$ values can be associated to two states: HIGH ($\geq \delta_{l,p}$) or LOW ($< \delta_{l,p}$), the following statistics are also generated and stored in the database:

- The probability $P_L^{l,p}(\delta_{l,p})$ of observing a LOW fittingness factor:

$$P_L^{l,p}(\delta_{l,p}) = \text{Prob}[F_{l,p} < \delta_{l,p}] \quad (5)$$

- The probability $P_H^{l,p}(\delta_{l,p})$ of observing a HIGH fittingness factor is then given by:

$$P_H^{l,p}(\delta_{l,p}) = 1 - P_L^{l,p}(\delta_{l,p}) \quad (6)$$

- The average of observed LOW fittingness factor values :

$$\overline{F_L^{l,p}} = E(F_{l,p} | F_{l,p} < \delta_{l,p}) \quad (7)$$

- The average of observed HIGH fittingness factor values:

$$\overline{F_H^{l,p}} = E(F_{l,p} | F_{l,p} \geq \delta_{l,p}) \quad (8)$$

Furthermore, in order to monitor fittingness factor variability, the following statistical metrics are considered:

- Given $F_{l,p}$ is LOW at a given time instant k , the probability that $F_{l,p}$ will be LOW at each time instant up to time $k+\Delta k$ defined as follows:

$$P_{L,L}^{l,p}(\Delta k, \delta_{l,p}) = \text{Prob}[F_{l,p}(k+j) < \delta_{l,p}, \forall j \in \{1, \dots, \Delta k\} | F_{l,p}(k) < \delta_{l,p}] \quad (9)$$

where $F_{l,p}(k)$ denotes the observed $F_{l,p}$ value at time k .

- Given $F_{l,p}$ is HIGH at a given time instant k , the probability that $F_{l,p}$ will be HIGH at each time instant up to time $k+\Delta k$ defined as follows:

$$P_{H,H}^{l,p}(\Delta k, \delta_{l,p}) = \text{Prob}[F_{l,p}(k+j) \geq \delta_{l,p}, \forall j \in \{1, \dots, \Delta k\} | F_{l,p}(k) \geq \delta_{l,p}] \quad (10)$$

The proposed fittingness factor variability metrics ($P_{L,L}^{l,p}$ and $P_{H,H}^{l,p}$) can be used to determine to which extent the fittingness factor is not likely to change after a certain time shift Δk .

b) Knowledge Manager

The KM plays a key role between the Knowledge Management and the Decision-Making domains of the proposed architecture. In this perspective, it manages the information retained in the KD in order to determine the knowledge about the environment that would be mostly relevant for supporting all decisions made by the decision-making entity.

On one side, the KM keeps an estimation of $F_{l,p}$ values based on the statistics available at the KD. These estimated values, denoted as $\hat{F}_{l,p}$ and obtained following Algorithm 1, are provided upon request to the decision-making module. The estimate $\hat{F}_{l,p}$ is determined based on whether the $F_{l,p}$ stored in the KD is likely to be the same that was obtained $\Delta k_{l,p}$ time units before (this is checked in the conditions of lines 5 and 11 with respect to the significance thresholds Thr_LOW and Thr_HIGH). In such case, $\hat{F}_{l,p}$ is set to the last measured value $F_{l,p}$ (lines 6 and 12). Otherwise, $\hat{F}_{l,p}$ is randomly set to either $\overline{F}_L^{l,p}$ or $\overline{F}_H^{l,p}$, the average $F_{l,p}$ values in the LOW and HIGH states, respectively, with probabilities $P_L^{l,p}(\delta_{l,p})$ and $1 - P_L^{l,p}(\delta_{l,p})$ (lines 8 and 14). Once all link/pool pairs are explored, the list of all estimated fittingness factor values ($\{\hat{F}_{l,p}\}$) is returned back to the decision-making entity (line 19).

On the other side, the KM captures relevant changes in these estimated values and informs the decision-making module for consideration.

Algorithm 1: Knowledge Manager (KM)

```

1: Function KM()
2: for  $l=1$  to  $L$  do
3:   for  $p=1$  to  $P$  do
4:     if ( $last\_F_{l,p}$  is LOW) do
5: if ( $P_{L,L}^{l,p}(\Delta k_{l,p}, \delta_{l,p}) \geq Thr\_LOW$ ) do
6:  $\hat{F}_{l,p} \leftarrow F_{l,p}$ ;
7: else
8: Estimate  $F_{l,p}$  as follows:

$$\hat{F}_{l,p} = \begin{cases} \overline{F}_L^{l,p} & \text{with probability } P_L^{l,p}(\delta_{l,p}) \\ \overline{F}_H^{l,p} & \text{with probability } 1 - P_L^{l,p}(\delta_{l,p}) \end{cases}$$

9:   end if
10: else
11: if ( $P_{H,H}^{l,p}(\Delta k_{l,p}, \delta_{l,p}) \geq Thr\_HIGH$ ) do
12:  $\hat{F}_{l,p} \leftarrow F_{l,p}$ ;
13: else
14: Estimate  $F_{l,p}$  as follows:

$$\hat{F}_{l,p} = \begin{cases} \overline{F}_L^{l,p} & \text{with probability } P_L^{l,p}(\delta_{l,p}) \\ \overline{F}_H^{l,p} & \text{with probability } 1 - P_L^{l,p}(\delta_{l,p}) \end{cases}$$

15:   end if
16: end if
17: end for
18: end for
19: return ( $\{\hat{F}_{l,p}\}$ );

```

2.4.2.5 Decision Making algorithms

The spectrum selection decision-making process aims to allocate, for a given application l , the best spectrum pool $p^*(l)$. In this respect, a proactive criterion is used. It selects the pool that maximizes the likelihood of observing a HIGH $F_{l,p}$ up to the end of the link session duration $T_{req,l}$. It is defined as follows:

$$p^*(l) = \arg \max_{p \in Av_Pools} \left(g(\hat{F}_{l,p}) \right) \quad (11)$$

where:

$$g(\hat{F}_{l,p}) = \begin{cases} P_{H,H}^{l,p} (\Delta k_{l,p} + T_{req,l}, \delta_{l,p}) & \text{if } \hat{F}_{l,p} \text{ is HIGH} \\ 0 & \text{if } \hat{F}_{l,p} \text{ is LOW} \end{cases} \quad (12)$$

In the very specific case of multiple channels fulfilling the maximization, the pool with the highest $\hat{F}_{l,p}$ is selected.

Notice that, unlike a greedy criterion that would simply maximize the instantaneous fittingness factor value a link can immediately get, the proactive criterion selects the pool that would be most likely to provide a HIGH fittingness factor value during the whole link session.

In what follows, both the spectrum selection and spectrum mobility functionalities of the decision-making process based on the above criterion are presented.

a) Spectrum Selection

Based on the fittingness factor values determined by the KM, the spectrum selection functionality selects a suitable spectrum pool for each radio link according to the Fittingness Factor-based Spectrum Selection algorithm described in Algorithm 2. Upon receiving a request for establishing a link l , the request is rejected if the set of available pools is empty (line 3). Otherwise, an estimation of all $F_{l,p}$ values is obtained from the KM (line 5). Based on provided $\hat{F}_{l,p}$ values, the best spectrum pool $p^*(l)$ is selected following the proactive criterion (line 6).

Algorithm 2: Fittingness Factor-based Spectrum Selection

```

1: if (service  $l$  request) do
2:   if (  $Av\_Pools = \emptyset$  ) do
3:     Reject request;
4:   else
5:     Get  $\{\hat{F}_{l,p}\}$  from the KM;
6:      $p^*(l) = \arg \max_{p \in Av\_Pools} \left( g(\hat{F}_{l,p}) \right)$ 
7:   end if
8: end if

```

b) Spectrum Mobility

In order to further adjust the behaviour to changes in spectrum resources suitability, the spectrum mobility functionality can be executed whenever better pools can be found for some services. Spectrum mobility is considered on a global perspective jointly optimizing all assignments in order to improve the overall pool usage efficiency.

As detailed by Algorithm 3, the proposed Fittingness Factor-based Spectrum Mobility is triggered whenever a previously selected pool by SS at link establishment is no longer the best in terms of $\hat{F}_{l,p}$ for the corresponding active link. This may happen whenever some active pools are released or experience some change in their $F_{l,p}$. Following both triggers, the KM is first called in order to get an estimation of all $F_{l,p}$ values ($\{\hat{F}_{l,p}\}$) (line 2). The algorithm then explores the list of currently active links ($Active_Links$) in the decreasing order of the required throughputs ($R_{req,l}$) in order to prioritize the neediest links. The decision to reconfigure or not each active link is based on a comparison between the actually used pool ($p^*(l)$) and the currently best pool in terms of $\hat{F}_{l,p}$ ($new_p^*(l)$) (line

7). Specifically, if $\hat{F}_{l,p^*(l)}$ is LOW and $\hat{F}_{l,new_p^*(l)}$ is HIGH, a SpHO from $p^*(l)$ to $new_p^*(l)$ is performed since $new_p^*(l)$ fits better link l . The same SpHO should be performed in case $p^*(l)$ is no longer available to link l after being preempted during previous reassignments (line 8). Once all active links are explored, the list of assigned pools is updated according to performed SpHOs (line 15).

Algorithm 3: Fittingness Factor-based Spectrum Mobility

```

1: if (service  $l^*$  ends OR change in any active  $F_{l,p}$ ) do
2: Get  $\{\hat{F}_{l,p}\}$  from the KM;
3: New_Assigned  $\leftarrow \emptyset$ ;
4: Sort Active_Links in the decreasing order of  $R_{req,l}$ ;
5: for  $l=1$  to |Active_Links| do
6:  $p^*(l) = \arg \max_{p \in Av\_Pools} (g(\hat{F}_{l,p}))$ 
7: if ( ( $\hat{F}_{l,p^*(l)}$  is LOW) AND ( $\hat{F}_{l,new\_p^*(l)}$  is HIGH)) OR
8: (( $p^*(l) \in New\_Assigned$ ) do
9:  $p^*(l) = new\_p^*(l)$ ;
10: New_Assigned  $\leftarrow New\_Assigned \cup \{new\_p^*(l)\}$ ;
11: else
12: New_Assigned  $\leftarrow New\_Assigned \cup \{p^*(l)\}$ ;
13: end if
14: end for
15: Assigned  $\leftarrow New\_Assigned$ ;
16: end if

```

2.4.3 Integration in OneFIT architecture

The functional entities that have been presented previously in section 2.4.2.3 have a direct mapping to the decision making and knowledge management entities at the CMON, as seen in Figure 9.

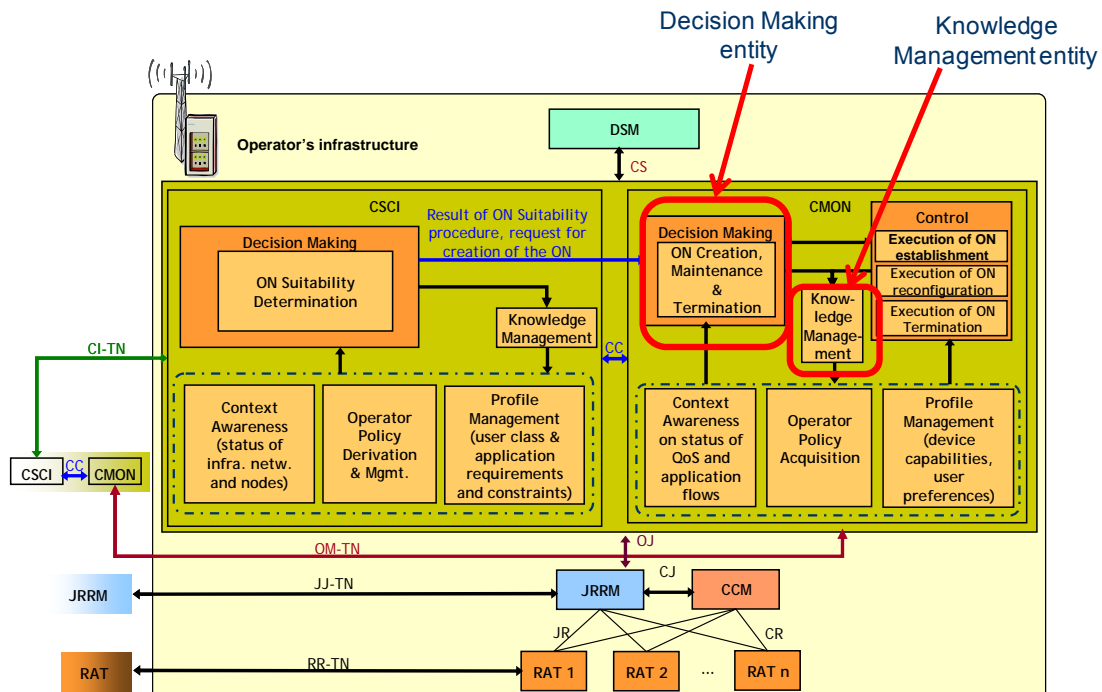


Figure 9: Mapping of the functional entities in the fittingness factor-based framework onto the OneFIT functional architecture

The previously described spectrum selection and spectrum mobility algorithms are associated with the ON creation and ON maintenance functionalities, respectively. The first one is intended to assign

a pool for a new incoming link to be established, while the second one intends to modify the current assignment whenever better pools can be found (either because some link has been released or because a change in the interference conditions has occurred). Both procedures can be supported by means of the C4MS messages that have been defined in D3.3 [7]. In particular, Figure 10 presents the associated signalling message flow related with the ON creation, based on the MIH implementation of C4MS. Note that the spectrum selection is executed at the infrastructure and the associated result is notified to the terminals in the link by means of the MIH_C4MS_ONN.response message. Similarly, Figure 11 presents the message sequence chart for the ON modification resulting from a change in the spectrum allocated to a link.

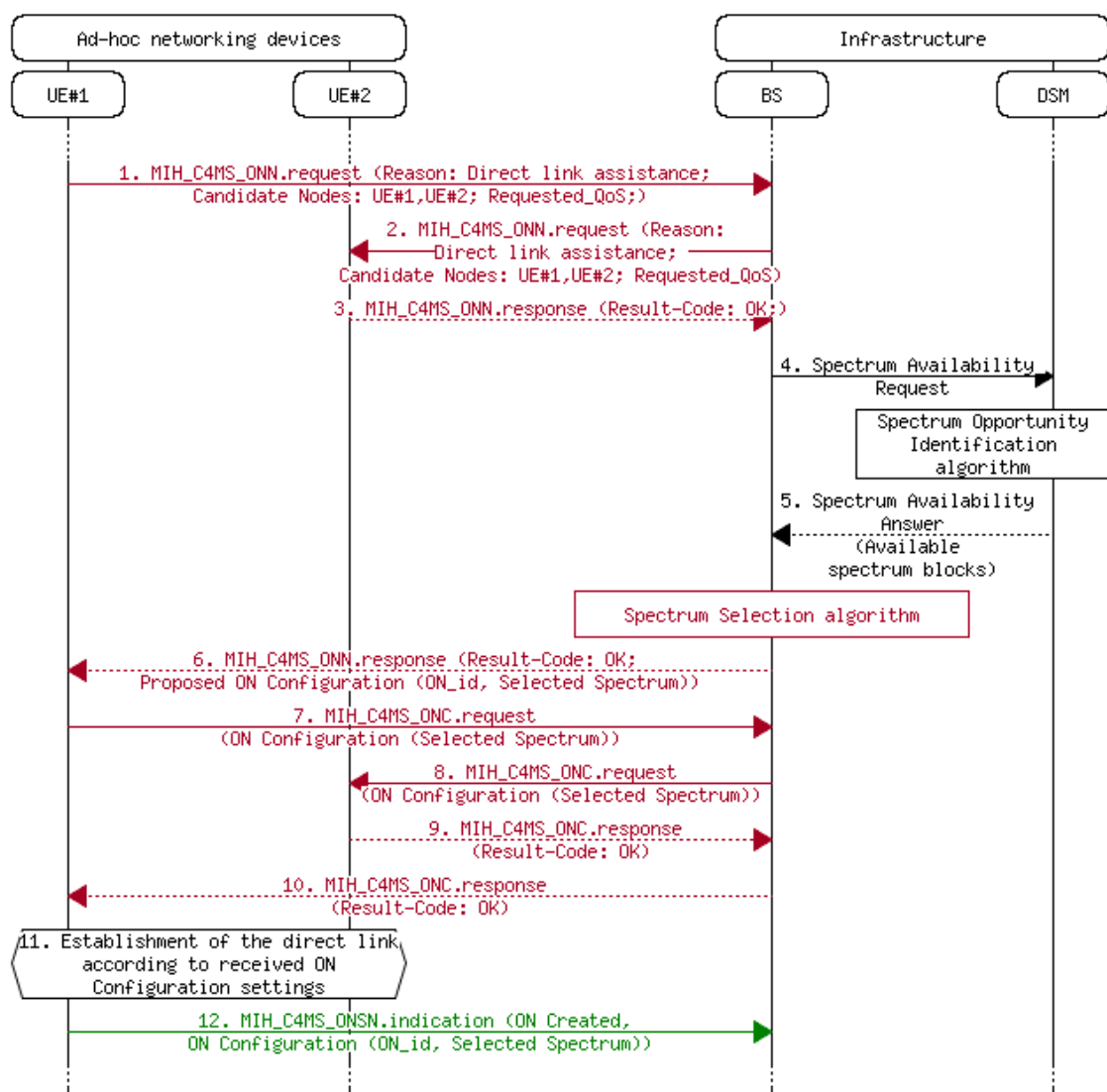


Figure 10: Signalling message flow for ON creation

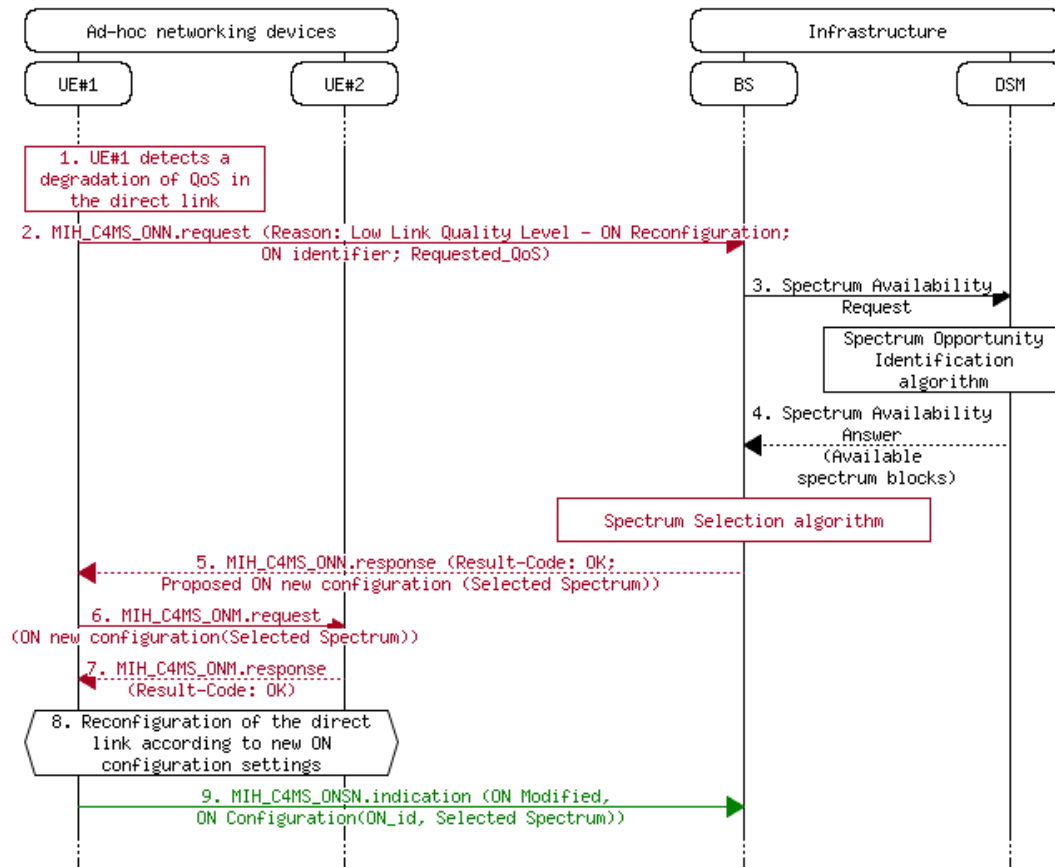


Figure 11: Signalling message flow for ON modification

2.5 Machine Learning based Knowledge Acquisition on Spectrum Usage

2.5.1 Problem formulation and algorithm concept

The proposed work is a novel distributed resource allocation scheme based on machine learning. The novelty of this work lies in its ability to learn from the surrounding radio environment. Each opportunistic access node should have the capability to sense its environment and tune its parameters accordingly, in order to operate under restrictions of avoiding interference to other secondary and primary users at the same time. Indeed, no information exchange needed. Each node assesses its environment and triggers a learning algorithm composing of a reward signal. With time, the algorithm learns channel occupancy state and thus which resources should be used in order to avoid interference as well as satisfying the required quality of service (QoS). This current formulation does not make use of spectrum usage history however our next candidate algorithm based on HMMs will be using available usage history and will be compared to the ML based approach described in the following sections.

2.5.2 Algorithm specification

The objective is to design and deploy an algorithm gives each access point AP (for example; femto-cells FCs) the ability to interact with the environment in order to adjust, learn, and build a probabilistic knowledge about the spectrum usage in a given geographical location. The acquired knowledge will be used to model the spectrum pools for opportunistic access by secondary nodes.

Based on this problem formulation, we present fully distributed reinforcement learning (RL) based algorithms. The proposed models are within the actor-critic methods, where the strategy playing the

role of the actor to select an action, and the estimated (predicted) value function is the critic. At each time step, the critic model evaluates the new state, based on the previous selected action by the actor model, in order to adjust the adopted its policy (mapping to the optimal action) toward maximizing a given objective.

Two learning strategies considered for the RL model:

- RL1: The modified Boltzmann-Gibbs reinforcement learning algorithm[49][50] where the strategy of action selection is modelled by Boltzmann-Gibbs scheme.
- RL2: The gradient-ascent TD reinforcement learning[51] where the strategy of action selection is modelled by sigmoid function.

The proposed techniques can be run in a centralized manner, so that to include a primary network policy, or distributed manner assuming that SUs have sufficient processing capabilities, where no collaboration is required.

For the problem formulation, we considered the following notations:

- Let $j = \{1, \dots, K\}$ be the set all APs (will be called as nodes), and $i = \{1, \dots, N\}$ is the number of resource blocks.
- Let $\{A_{t,j}\}$ be the set of actions taken by the j^{th} node on all resource blocks at each time step t , defined as a binary $1 \times N$ vector $A_{t,j} = \{a_{t,j}^1, \dots, a_{t,j}^N\}$, where $a_{t,j}^i \in \{0,1\} \forall i \forall j$.
- Action $a_{t,j}^i = \{1\}$ means the sub-channel i not utilized and can be used by the j^{th} node. While, $a_{t,j}^i = \{0\}$ means that the sub-channel i is occupied.
- $\{A_t\}_{\forall j}$: Is the different sets of actions of all nodes (the action profile), defined as $N \times J$ matrix.
- $p_{t,j}^i$: Defined as the probability distribution of the j^{th} node over his actions on the i^{th} sub-channel, known as the strategy, where $p_{t,j}^i \in \Delta(a_{t,j}^i) \forall i$, and $\Delta(a_{t,j}^i) = \Delta(\{0,1\}) = \{(p(0), p(1)) \in \mathbb{R}_+^N, \sum_{\forall a} p_a = 1\}$.
- $\{\pi_{t,j}\}_a$: Defined as the strategies set taken by the j^{th} node to select action a over all sub-channels, represented by $1 \times N$ vector $\pi_{t,j} = \{p_{a,i}, \dots, p_{a,N}\}$. For example; $\{\pi_{t,j}\}_1$ is the strategy (probability distribution) of taking action $\{1\}$ for all sub-channels.
- $\{\pi_t\}_{\forall j}$: Is the strategy profile of all nodes, defined as $N \times J$ matrix.
- The variable $(u_{t,j})_A^\delta$ is the received realization (payoff) at time t when the j^{th} node interact with the environment selecting action $\{A_{t,j}\}$, which depends on the state of the network \mathcal{S} and the action profile $\{A_t\}_{\forall j}$.

2.5.2.1 Algorithm inputs and outputs

The main assumptions considered in the scenario can be summarized as follows:

- All possible action sets $\{A_j\}$ not necessarily to be known in advance by the node, but will be explored and exploited with time, by the individual probability $p_{t,j}^i$.
- At each time step, node j knows its own actions set $\{A_{t,j}\}$, but not the action selected by other nodes $\{A_{t,-j}\}$. On other words, the action profile $\{A_t\}_{\forall j}$ is not known by each individual nodes.

- At each time step, node j knows its received payoff $(u_{t,j})_A^S$ but not the other nodes received payoff $(u_{t,-j})_A^S$.
- No collaboration required between primary and secondary networks, and neither between secondary APs.
- No large memory required to store historical data; only one time step back is considered.

The set of actions $\{A_{t,j}\}$ taken by the j^{th} node on all sub-channels represents the spectrum pools at each time t . Indeed, $\{a_{t,j}^i = 1\}$ means that the i^{th} sub channel is not utilized by primary network, while $\{a_{t,j}^i = 0\}$ means that the sub channel is occupied, either by primary network, or other secondary nodes.

The expected output of the algorithm is the utilization probability $(p_{t,j}^i)$ at each time step t , sub-channel i and AP j . The utilization probability is defined as the probability of the sub-channel to be not utilized by LTE RAN. So, sub-channels with high utilization probability are most likely to be free for opportunistic access by secondary nodes.

2.5.2.2 Algorithm operation and functional entities

In this section, we present dynamic solution using methods from reinforcement learning RL1 and RL2. The dynamic solution can be described as follows:

- Each node has an initial configuration of its strategy $\pi_{0,j}$.
- Each node selects set of actions $\{a_{0,j}\} \in A_j$ based on the strategy $\pi_{0,j}$.
- At time t , each node receives a payoff $(u_{t,j})_A^S$ corresponding to the selected action profile $\{A_{t-1}\}_{\forall j}$ of all nodes and network status S_t . Then each node:
 - Estimate his utility vector $\hat{u}_{t+1,j}$ according to the learning strategy given in equations (1) and (2).
 - Update his strategy $\pi_{t,j}$ according to updating rule given in (RL_1) and (RL_2).
- For the next stage, each node select set of actions $\{a_{t+1,j}\} \in A_j$ based on the updated strategy $\pi_{t,j}$.
- Repeat learning iteration.

RL_1: The modified Boltzmann-Gibbs RL algorithm:

After receiving payoff $(u_{t,j})_A^S$, each j node update his strategy $\{\pi_{t,j}\}_a$ of taking action a using the Boltzmann-Gibbs scheme, as follows:

$$\{\pi_{t,j}\}_a = \{p_{a,1}(j, t, \omega, \tau), \dots, p_{a,N}(j, t, \omega, \tau)\} = \left\{ \frac{e^{\frac{\omega_{1,a}}{\tau}}}{\sum_{\forall a} e^{\frac{\omega_{1,a}}{\tau}}}, \dots, \frac{e^{\frac{\omega_{N,a}}{\tau}}}{\sum_{\forall a} e^{\frac{\omega_{N,a}}{\tau}}} \right\} \quad (13)$$

where $\omega_{i,a}$ is the propensity of action a at the i^{th} sub-channel, and τ is a positive parameter. The propensity of action $\omega_{i,a}$ act as an aspiration levels, following the updating rule:

$$\omega_{i,a}(t+1) = (1 - \varphi)\omega_{i,a}(t) + \mathcal{G}(\varepsilon, i, j, t) \quad (14)$$

$$\mathcal{G}(\varepsilon, i, j, t) = \begin{cases} u_{t,j}(1 - \varepsilon), & \text{if } a_{t,j}^i = a \\ u_{t,j} \frac{\varepsilon}{N_a - 1}, & \text{if } a_{t,j}^i \neq a \end{cases} \quad (15)$$

where φ is called the recency parameter ($0 < \varphi < 1$). As φ approaches 0, approximately equal weights placed on all rewards $(u_{t,j})_A^S$ received over time. While ε is the experimentation parameter ($0 < \varepsilon < 1$), as ε approaches 0, reward resulting from chosen action $a_{t,j}^i$ is attributed only to $a_{t,j}^i$, implying only propensity $\omega_{i,a}$ of the selected action $a_{t,j}^i$ is updated.

The actions for the next step will be generated based on a Bernoulli binary generator given by means of each node strategy $\{\pi_{t,j}\}_a$, as shown below:

$$a_{t,j}^i(t+1) = \text{Ber}(p_{a,i}(j, t, \omega, \tau)) \quad \text{for } \forall i \text{ and } \forall j \quad (16)$$

RL_2: The gradient-ascent TD RL:

The estimated reward signal can be updated incrementally by applying the following update rule every time the action was executed:

$$\hat{u}_{t+1,j} = \hat{u}_{t,j} + \lambda(u_{t,j} - \hat{u}_{t,j}) \quad (17)$$

where λ is a constant step-size parameter, and $\hat{u}_{t,j}$ is the average reward signal at time step t .

The exploration strategy $\{\pi_{t,j}\}_a$, or the probability of selecting action a at time t following a Sigmoid function given by :

$$\{\pi_{t,j}\}_a = \{p_{a,1}(j, t, \omega, \tau), \dots, p_{a,N}(j, t, \omega, \tau)\} = \left\{ \frac{1}{1 + e^{-\frac{\omega_{1,a}}{\tau}}}, \dots, \frac{1}{1 + e^{-\frac{\omega_{N,a}}{\tau}}} \right\} \quad (18)$$

where $\omega_{i,a}$ is the weights of taking action a , and τ is a positive parameter.

Each node j update his strategy $\{\pi_{t,j}\}_a$ of undertaking the selected action a by adjusting the probability weights $\omega_{i,a}$ according to the following equation:

$$\omega_{i,a}(t+1) = \omega_{i,a}(t) + \alpha(1 - \lambda)(\hat{u}_{t,j} - u_{t,j}) \nabla_{\omega} \text{Sigm}(i, j, \omega, \tau) \quad (19)$$

where α is the node learning rate ($0 < \alpha < 1$), and $\nabla_{\omega} \text{Sigm}(i, j, \omega, \tau)$ is the gradient of the sigmoid function with respect to probability weights $\omega_{i,a}$.

Finally, the actions for the next step will be generated based on a Bernoulli binary generator given by means of each node strategy $\{\pi_{t,j}\}_a$, as shown below:

$$a_{t,j}^i(t+1) = \text{Ber}(p_{a,i}(j, t, \omega, \tau)) \quad \text{for } \forall i \text{ and } \forall j \quad (20)$$

2.5.3 Integration in OneFIT architecture

Figure 12 below depicts a mapping of the functionalities of the algorithm to the OneFIT function architecture and the functionalities entities as defined in D2.2 [3]. The algorithm is associated with the ON creation & maintenance phases. The procedure can be supported by means of the C4MS messages that have been defined in D3.3 [7].

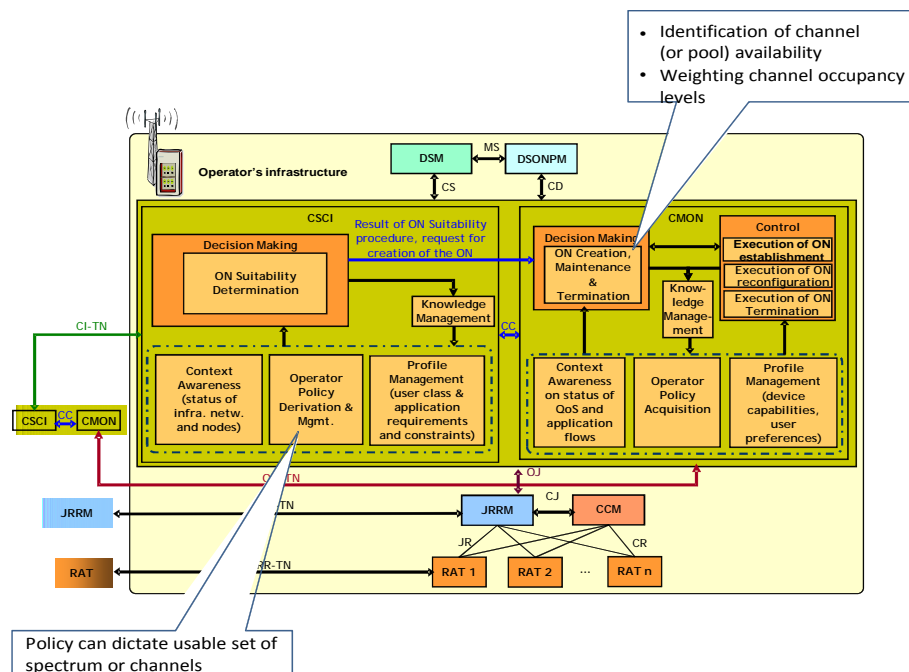


Figure 12: Mapping of the functional entities in the ML approach to spectrum knowledge acquisition, onto the OneFIT functional architecture

2.6 Techniques for Aggregation of Available Spectrum Bands/Fragments

2.6.1 Problem formulation and algorithm concept

The problem considered here is the approach for spectrum selection with spectrum aggregation (SA) capabilities. When it is difficult to support enough bandwidth with contiguous available spectrum, multiple small spectrum fragments (sub-channels) can be exploited to yield a (virtual) single channel by spectrum aggregation. Spectrum aggregation can be classified into three types:

- Intra-band contiguous spectrum aggregation: when multiple sub-channels are adjacent to each other within the same band.
- Intra-band non-contiguous aggregation: when multiple sub-channels within the same band are used in a non-contiguous manner.
- Inter-band non-contiguous aggregation: when multiple sub-channels are separated along the frequency band (e.g. one sub-channel in 2GHz and another in 800MHz are aggregated).

Since the spectrum allocation for an operator is often dispersed along the frequency bands with large frequency separation and the spectrum availability in low frequency band (<4GHz) is scarce, it could be difficult to support large transmission bandwidth with contiguous CA. Therefore, inter-band non-contiguous CA could provide a practical approach to fully utilize the current spectrum resources. However, the radio channel characteristics and transmission performance vary a lot at different frequency bands. The impact of these variations should be minimized and communication over separate bands implies a substantial complexity burden on the UE [23] in terms of signalling overhead, power consumptions and so on. It must therefore be clarified that inter-band SA should be exploited only when the intra-band SA is not available.

When the spectrum is highly fragmented, it would require the excessive filtering/or guard bands to protect adjacent users. In addition, the node is allocated the channel composed of many small sub-channels and increases in the number of sub-channels in the virtual channel means increase in the channel search time [24]. Setting a lower bound on the usable fragment size for aggregation could be useful in order to prevent higher system complexity caused by spectrum fragmentation [25].

Regarding the spectrum selection for aggregate channels, three different aggregation schemes based on *firstfit*, *bestfit* and *worstfit* are compared with those performances in terms of the number of sub-channels and spectrum utilization level under the hardware constraint of the spectrum aggregation range [26]. By the simulation results, it is shown that the spectrum aggregation algorithm based on *worstfit* scheme which prefers the configurations of an aggregate channel composed of less sub-channels by choosing wider sub-channels outperforms in terms of spectrum utilization. It is also shown that the spectrum utilization level can be enhanced by reducing the number of sub-channels under the constraint of limited spectrum aggregation range in the dynamic spectrum allocation scenario. Thus, the number of sub-channels composing the aggregate channels should be small. When the spectrum is allocated to users having the spectrum aggregation capability, the preference of aggregation can be ordered as following: intra-band contiguous aggregation, intra-band non-contiguous aggregation and inter-band aggregation.

When spectrum is allocated to users with spectrum aggregation capability, many factors should be considered simultaneously. First, since maximizing the total throughput by efficient spectrum utilization is still important, the sub-channel with the highest quality can be preferred. Second, in the opportunistic spectrum access, since channel switching caused by a returning PU leads to system overhead, selection of the channel with the least-likelihood for the appearance of a PU is advantageous. Finally, the aggregate channel which is composed of less number of sub-channels with the type of spectrum aggregation with less complexity can be selected. The proposed algorithm makes use of the utility-based approach for these three objectives. While the algorithm uses the spectrum availability obtained from the spectrum opportunity identification as the input, it also exploits the historical information on PU activity and the available bit rate of each sub-channel based on radio characteristics. The multiple objectives are integrated into a weighted sum utility function in the proposed algorithm. The weight associated with each objective can be set differently (typically done manually) depending on the metric to be optimized. In the proposed algorithm, an automatic mechanism for setting weights is included. The algorithm including the learning module allows for automated (no manual intervention) adaptable setting of objective-function weights depending on the environment changes.

Within the ON lifecycle, the spectrum allocation with aggregation considered in this section is for the creation and maintenance phase. When new link needs to be established in an ON, this algorithm is performed to find the proper aggregate channel. In addition, whenever there are needs of change of channels of links (i.e. spectrum availability), the proposed algorithm is executed for the channel switching.

2.6.2 Algorithm specification

2.6.2.1 Algorithm inputs and outputs

The list of inputs used by the proposed aggregation algorithm to find proper spectrum for links are the following ones.

- Information on spectrum availability: This will be provided by the spectrum opportunity identification. It consists of the list of (centre frequency, bandwidth) of each spectrum hole. This information can be utilized to identify the spectrum occupancy pattern by the primary users' spectrum usage.
- Supportable bit rate of the all candidate links from each user
- Node's capability of spectrum aggregation
- QoS requirement of the nodes: required throughput and service time
- Information on current spectrum allocation: Currently allocated spectrum to links in the ON. This information is kept by the function of spectrum aggregation algorithm.

With the inputs, the algorithm will find the proper aggregate spectrum to links.

2.6.2.2 Algorithm operation and functional entities

In order to perform the spectrum aggregation and allocation considering multi-objective, the operation of the proposed algorithm is based on the following framework.

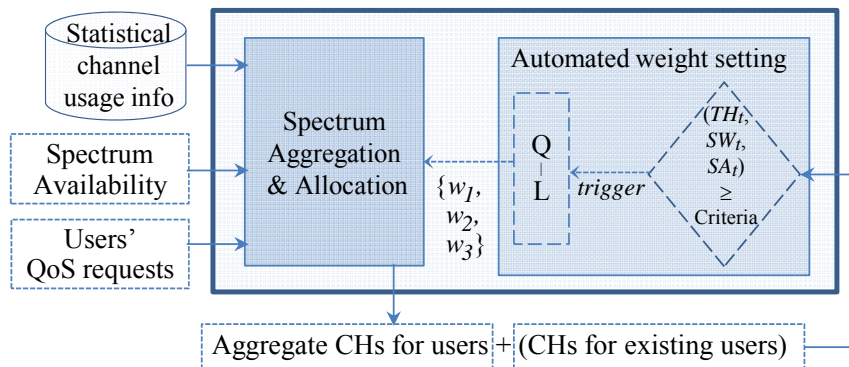


Figure 13: The framework of spectrum aggregation & allocation using Reinforcement learning

- **Multi-objective utility-based spectrum aggregation and allocation:** The proposed aggregation algorithm considers three objective: 1) to maximize the total throughput, 2) to minimize the channel switching, and 3) to reduce the spectrum aggregation complexity. These three objectives are integrated into a weighted sum utility function. The spectrum is assumed to be channelized as the basic unit and the availability of spectrum opportunities is varying from the primary user's spectrum usage. It is also assumed that spectrum occupancy status does not change during spectrum aggregation and allocation intervals. As well as spectrum availability, the transmission rates based on channel quality for all nodes on all sub-channels are assumed to be also known. Information on statistical characterisation channel availability is stored in a database such as Radio Environment Map (REM) and can be accessed by secondary users to allocate the channel of the least-likelihood for the appearance of PUs. Multiple sub-channels can be aggregated to satisfy the secondary user's throughput requirement. While spectrum aggregation of sub-channels in the same band are preferred, the aggregated channels with less number of sub-channels is preferred as found in [26] as described in 2.6.2.3.
- **Automated weight setting by the learning technique:** While the multi-objective spectrum aggregation approach exploits the weighted sum approach, the optimal weights setting can be different depending on the interested performance metric. The system is assumed to have set/pre-defined thresholds for each performance metric based on system level Key Performance Indicators (KPIs) to be met. While the spectrum is allocated to users, the performance of each objective is monitored (Monitoring). In case that the monitored performance is not met/thresholds crossed, the learning module is triggered (Triggering). As a result of the learning process (Learning), the set of optimal weight vector is found (Selection) and used by the spectrum aggregation algorithm. In order to find the proper weight setting for the different environment, the MTLS process (i.e. Monitoring → Triggering → Learning → Selection) repeats.

2.6.2.3 Utility-based multi-objective spectrum aggregation

The spectrum allocation problem is formulated by the following optimization function.

$$A^* = \arg \max_{N, M} F(U) \quad (21)$$

where N is the number of nodes and M is the number of available channels. The total utility value is denoted as the sum-weighted function with the weight vector for each objectives $\{w_1, w_2, w_3\}$.

$$F(U) = \sum_{k=1}^3 w_k \cdot A \cdot u_k = \sum_{k=1}^3 w_k \cdot \sum_{i=1}^N \sum_{j=1}^M a_{i,j} \cdot u_{k,i,j} \quad (22)$$

where $a_{i,j}$ is the binary channel assignment indicator and denotes whether user i occupies channel j . If $a_{i,j} = 1$, channel j is assigned to user i , otherwise, is not. $u_{k,i,j}$ is the utility value of k^{th} objective when j^{th} channel is allocated to i^{th} user, and the weight of the k^{th} objective is w_k .

$$\sum_{k=1}^3 w_k = 1, 0 < w_k < 1 \quad (23)$$

By the utility function of each objective, the utility value of each sub-channels for each users are calculated. The aggregation algorithm allocates aggregate channel for each spectrum request to maximize the global utility value achievable from the allocated resources. Each objective is weighted by its importance and $u_{k,i,j}$ is normalized and the maximum value of sum of utility values is 1. The set of allocated channel for each user satisfy the user's QoS requirement, required throughput.

The utility value of each objective is calculated by the utility function of each objective as follows.

1) To maximize the spectrum utilization, $u_{1,i,j}$

In order to allocate the channel with best quality to users, we calculate the utility value and the modified hyperbolic tangent function explained in [26] is exploited.

$$f(x, x_0; \eta, \sigma) = \frac{1}{2} \left\{ \tanh \left[\log \left(\frac{x}{x_0} \right) - \eta \right] \sigma + 1 \right\} \quad (24)$$

The threshold (η) and spread parameter (σ) are chosen such that i) the utility is 0.95 when the metric (x) achieves the target (x_0) and ii) the utility is 0.05 when the metric is one decade away. This function is monotonic and bounded by zero and one. By using this function, the utility value for the first objective is calculated as follows.

$$u_{1,i,j} = f(R_{i,j}, R_{\max}; \eta, \sigma) \quad (25)$$

where $R_{i,j}$ is the achievable rate of channel j used by a node i and R_{\max} is the maximum value of $R_{i,j}$ for all users and all channels. Since higher value is calculated for the pair of user and channel of better quality, this objective will contribute to enhance the overall throughput.

2) To reduce channel switching, $u_{2,i,j}$

The identified primary behaviour is exploited to, which is to perform a proactive spectrum selection for the channel of the least-likelihood for the appearance of a PU and to reduce the channel switching. The estimated remaining idle time, $T_{\text{Re_idle_}j}$ can be calculated with average duration of the observed OFF period, $E(\text{OFF}_j)$ by using the information on historical PU activity as well as the so-far observed duration of the current OFF period, $T_{\text{Cnt_idle_}j}$. The utility values for all idle channels and for all users are also calculated with the modified hyperbolic tangent function.

$$u_{2,i,j} = f(T_{\text{Re_Idle_}j}, T_{\text{Re_Idle_}j_{\max}}; \eta, \sigma) \quad (26)$$

Since the utility value of this objective depends on the estimated remaining idle time, the utility values of the certain channel are the same for all users, that is, $u_{2,i-1,j} = u_{2,i,j}$ for $2 \leq i \leq N$.

3) To reduce the complexity of the spectrum aggregation, $u_{3,i,j}$

When spectrum is aggregated for users' resource request, the preference of aggregation can be ordered as following: the contiguous spectrum without aggregation, intra-band contiguous aggregation, inter-band non-contiguous aggregation and inter-band aggregation. When the algorithm considers a channel j for the user i , it decides the type of spectrum aggregation based on the status of the adjacent channel $j-1$ and $j+1$. If the adjacent channel is already allocated to the user, it can become the most promising choice. In this case, the utility value becomes 0.95. If the aggregation type is non-contiguous intra-band spectrum aggregation, 0.5 will be allocated as the utility value. For the case of the most complex case, inter-band spectrum aggregation, 0.05 is given to the utility value for spectrum aggregation.

$$u_{3,i,j} = \{0.95, 0.5, 0.05\}, \forall i, j \quad (27)$$

The problem of spectrum allocation with aggregation based on the utility function of multi-objective is formulated as following.

$$F(U) = \sum_{i=1}^N \sum_{j=1}^M a_{i,j} \cdot (w_1 u_{1,i,j} + w_2 u_{2,i,j} + w_3 u_{3,i,j}) \quad (28)$$

The proposed algorithm assigns sequentially each sub channel that will experience the higher utility to the node until the set of allocated channels satisfies users' requested throughput, TH_{req} . Consequently, it is aimed at maximizing the global utility values achievable with the available resources.

Algorithm 4: Utility-based multi-objective spectrum aggregation

1: if(link l_i with TH_{req}^i , $1 \leq i \leq N$ & available channels $CH_{avail} = \{CH_j, 1 \leq j \leq M\}$) do

2: Aggregate_CH(l_i) $\leftarrow \emptyset$, Remained_TH(l_i) = TH_{req}^i , for $1 \leq i \leq N$

2: for $i=1$ to N do

3: for $j=1$ to M do

4: utility(i, j) = $w_1 \times u_{1,i,j} + w_2 \times u_{2,i,j} + w_3 \times u_{3,i,j}$;

5: end for

6: end for

7: while($CH_{avail} \neq \emptyset$ & Remained_TH $\neq \emptyset$) do

8: (i^*, j^*) = arg max (utility(i, j));

9: Aggregate_CH(i^*) \leftarrow Aggregate_CH(i^*) $\cup \{j^*\}$;

10: Remained_TH(i^*) = Remained_TH(i^*) - R_{i^*,j^*} ;

11: $CH_{avail} = CH_{avail} - \{j^*\}$;

12: if(Remained_TH(j^*) < 0) utility(i^*, j^*) = 0; end

13: end while

14: end if

2.6.2.4 Automated weight setting by the learning technique

The weights associated with each objective can be different (typically done manually) depending on the performance metric of interest. In the proposed algorithm, the automated mechanism for setting weights is included so that adaptable setting (without manual intervention) of objective-function weights is possible depending on the environment changes. The system continuously monitors the performance of each individual objective and decides to trigger the learning module for the case of the degraded performance. As a result of learning, the optimal weight values are chosen and applied to the spectrum aggregation method. Thus, the weight values are adaptively set/learned based on the radio environment encountered so that the performance of each objective remains close as possible to the pre-defined thresholds.

The module for automatic selection of weights is implemented with the Q-learning, an off-policy Reinforcement Learning (RL) algorithm described in [26]. The learning model to decide the weight values comprises the possible states of the environment S , the set of possible actions A , the reward function R , and the policy $\pi: S \rightarrow A$. Q-learning learns the optimal policy through simple Q-value iterations to take note of recent policy success/failure as feedback and the weighted average of past values observed. In the considered scenario, the elements of learning model are defined as follows:

- 1) **States:** The state is monitored as the average performance including total throughput TH_m , channel switching SW_m , and the number of bands for aggregate channels SA_m .

$$s_t = (TH_m, SW_m, SA_m) \quad (29)$$

- 2) **Actions:** the weights vector set

$$a_t = (w_1, w_2, w_3) \text{ where } 0 < w_i < 1 \text{ and } w_1 + w_2 + w_3 = 1 \quad (30)$$

- 3) **Rewards:** The reward of applying a certain set of weights is the satisfaction degree compared to the pre-defined threshold. It is calculated by the following Equation.

$$r_t = 1 + \max \left\{ 0, \frac{TH_t}{TH_C} - 1 \right\} + \max \left\{ 0, 1 - \frac{SW_t}{SW_C} \right\} + \max \left\{ 0, 1 - \frac{SA_t}{SA_C} \right\} \quad (31)$$

When the achieved performance (i.e. TH_t , SW_t , and SA_t) meets the threshold (i.e. TH_C , SW_C , and SA_C), the reward is one as the maximum. The reward reflects the satisfaction degree of the achieved results to the predefined threshold.

Algorithm 5: Optimal weight setting with learning technique

```

1: Do monitor the spectrum aggregation performance based on Algorithm 4  $\rightarrow TH_m, SW_m, SA_m$ 
2: if ( $TH_m < TH_C$  ||  $SW_m > SW_C$  ||  $SA_m > SA_C$ ) do
3:   generate Q table  $\leftarrow \emptyset$ ;
4:   select the action  $a_t = (w_1, w_2, w_3)_t$ 
5:   for  $i=1$  to  $TIMES\_LEARNING$  do
6:     do the spectrum aggregation & allocation algorithm with  $(w_1, w_2, w_3)_t$  (in algorithm 4)
7:     store the monitored performance of the spectrum aggregation & allocation  $\{TH_t, SW_t, SA_t\}$ 
8:     Calculate the reward,  $r_t$ 
9:     Select the next action
10:    update Q table
11:  end for
12:  Select the optimal weights =  $\arg \max(Q)$ ;
13: end if

```

2.6.3 Integration in OneFIT architecture

Figure 14 provides a mapping of the functionalities of spectrum aggregation and allocation to the OneFIT function architecture and the functionalities entities as defined in D2.2 [3]. The aforementioned spectrum aggregation algorithm associates with the ON creation & maintenance phases. The procedure can be supported by means of the C4MS messages that have been defined in D3.3 [7]. In particular, Figure 15 and Figure 16 presents the associated message sequence charts for the spectrum aggregation with aggregation in On creation & maintenance.

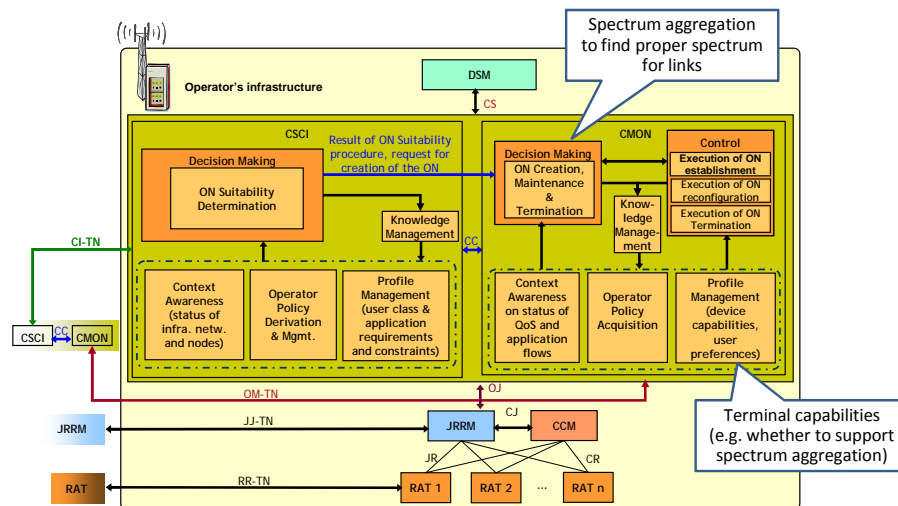


Figure 14: Mapping of the functional entities in the spectrum aggregation and allocation onto the OneFIT functional architecture

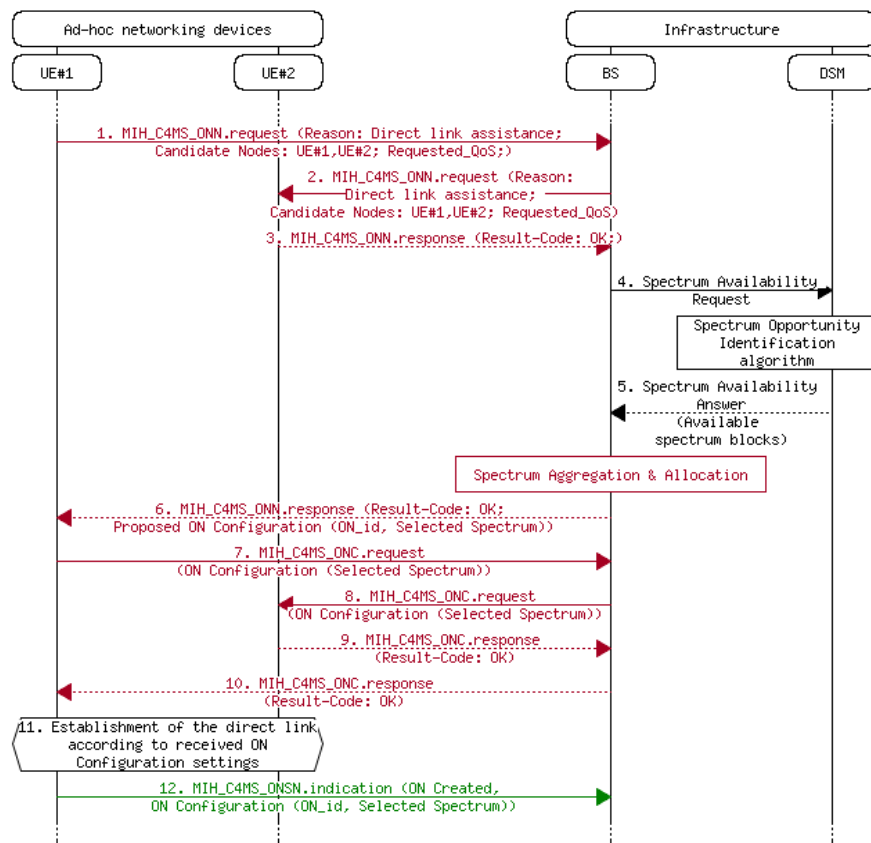


Figure 15: Message Sequence Chart for the spectrum aggregation for ON creation phase

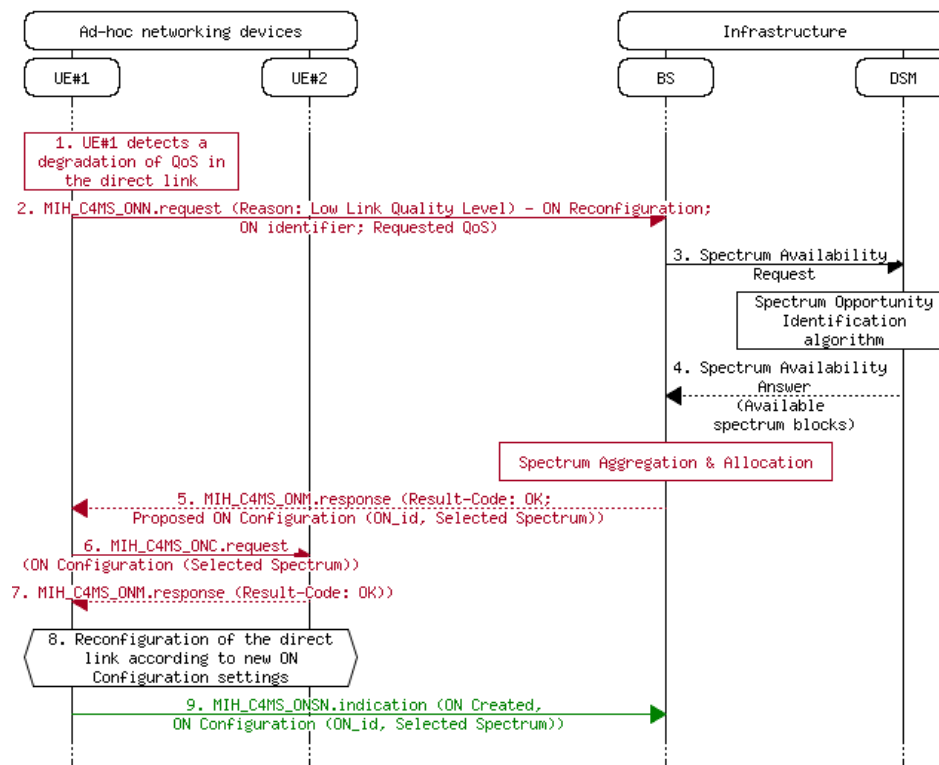


Figure 16: Message Sequence Chart for the spectrum aggregation for ON modification phase

2.7 Algorithm on knowledge-based suitability determination and selection of nodes and routes

2.7.1 Problem formulation and algorithm concept

Two main approaches have been proposed for the creation of ONs taking into consideration multiple parameters. These approaches are focused on the capacity extension through neighboring terminals and the selection of nodes through a fitness value evaluation which could be considered for the coverage or the capacity extension scenarios (scenarios 1 and 2 as described in [2]).

2.7.1.1 Capacity extension of the infrastructure through neighboring terminals

The algorithm is executed in the infrastructure side and more specifically in a congested base station which needs to solve the problem of congestion. It is triggered whenever a congestion situation occurs in the infrastructure and makes decisions on the establishment of routes which will redirect traffic from the congested service area into non-congested ones. The proposed solution of the algorithm is based on the Ford-Fulkerson maximum flow algorithm and it is assumed that each terminal in the congested service area creates one application flow which can be redirected through neighboring terminals (e.g., which are in range of a typical 802.11b/g connection) to alternate, non-congested BSs.

2.7.1.2 Selection of nodes through a fitness value evaluation

According to the OneFIT concept, ONs are created in an infrastructure-less manner under the supervision of the operator and include numerous network-enabled elements. To ensure application provisioning in an acceptable QoS level, the selection of the proper nodes, among all discovered nodes in the vicinity is rather essential. As a result, this approach proposes a mechanism for selecting nodes that will participate to the ON. The selection mechanism is based on a fitness function which is a weighted, linear formula which takes into consideration the following:

- Candidate node's energy level;
- Candidate's node availability level which shall take into account:
 - capabilities (e.g. available interfaces/supported RATs, support of ON);
 - status of each node in terms of communication resources (e.g. status of the active links), storage (e.g. available buffer/cache), computing resources (e.g. available memory);
 - node's location;
 - the ability of a node to support a requested application;
- Candidate node's delivery probability (i.e., ratio of successfully transmitted packets to messages received by a node).

For example, if a neighboring node does not have available buffer/cache because it is loaded with data packets waiting to be delivered, then the node is considered as unavailable, despite the fact that in terms of other parameters (e.g. energy) that node may perform in an acceptable level.

2.7.2 Algorithm specification

2.7.2.1 Capacity extension of the infrastructure through neighboring terminals

The set of congested BSs is denoted as B_1 while the set of non-congested BSs is denoted as B_2 . Let T_c be the set of terminals that are connected to the congested BSs (represented by B_1 set). Also, let $T_{cm} \subseteq T_c$ be the set of terminals which have ON capabilities. Let T_{nc} be the set of terminals that are connected to the non-congested BSs (represented by B_2 set). Let graph $G(V, E)$ be a directed graph, consistent or not, where $V = T_{cm} \cup T_{nc} \cup B_1 \cup B_2$ and E is the set of links among the nodes of the graph G . Let P be a set of paths from terminals $t \in T_{cm}$ to BSs $b \in B_1 \cup B_2$ that were discovered from the execution of breadth-first search for graph G . Each path $p \in P$ includes a starting point $t_p \in T_{cm}$, an ending point $b_p \in B_1 \cup B_2$ and a set of links $L_p \subseteq E$. For each $p \in P$ the starting point t_p is connected with a virtual link to a "super-source" (ss) virtual node and the ending point b_p is connected with a virtual link to a "super-destination" (sd) virtual node. Each link $l(u, v) \in L_p$ has a starting point $u \in T_{cm} \cup T_{nc} \cup \{ss\}$, an ending point $v \in V \cup \{sd\}$, the RAT that is used for the transmission and the capacity $cap[l(u, v)] \in \mathbb{N} \setminus \{0\}$ where \mathbb{N} is the set of natural numbers. The capacity is considered as the number of simultaneous traffic flows that can be served through this link. Furthermore, each link $l(ss, t)$, $t \in T_{cm}$ (from the "super-source" to a terminal in the congested area) has a capacity $cap[l(u, v)] = 1$, because through this link only one flow f is pushed. A flow $f[l(u, v)]$ represents the number of terminals that are being relayed through link $l(u, v)$. All the BSs are connected to a "super-destination" node (sd) which is also a virtual node. The algorithm takes as input a graph G and the sets B_1 , B_2 and T_{cm} .

The input of the algorithm consists of the following:

- Sets of congested and non-congested BSs
- Set of terminals in the congested area that have ON capabilities and can be redirected to alternate BSs
- Paths from source to destination. Each path originates from a 'virtual' source where terminals with ON capabilities in the congested area are connected and ends to a 'virtual' destination where BSs are connected.

At the initialization phase the link capacities are estimated. Their values derive from parameters such as the RAT of the link, the quality of the link, operator policies and users' profiles. In addition, the flows of all links are initialized to zero. Then the set P is created by the paths that are being discovered by the breadth-first search algorithm which yields the shortest path. The algorithm runs for each $p \in P$ for which there is a link where more flow can be directed. As soon as all possible paths are saturated (i.e. there is no path with available capacity anymore and flow could not be pushed to it) the algorithm finalizes. The algorithm procedure is given by the pseudo-code that follows:

Algorithm 6: Capacity extension of the infrastructure through neighbouring terminals

```

1. Estimate  $cap[l(u,v)] \forall l(u,v)$ 
2. Initialize  $f[l(u,v)] \leftarrow 0 \forall l(u,v)$ 
3. Creation of set  $P$  through the breadth-first search
4. for each  $p \in P \mid \exists l(u,v) \in L_p : f[l(u,v)] < cap[l(u,v)] \{$ 
   $cap(p) \leftarrow \min \{ cap[l(u,v)] \} \forall l(u,v) \in L_p$ 
   $f[l(u,v)] \leftarrow \{ f[l(u,v)] + cap(p) \} \forall l(u,v) \in L_p$ 
  Update the residual capacities of the rest of the links of  $p$ 
   $\}$ 

```

where

$G(V,E)$	Graph G , with V nodes and E the set of links among the nodes of the graph
P	Set of paths
L_p	Set of links where $L_p \subseteq E$
$l(u,v)$	Link between u and v where $l(u,v) \in L_p$
$cap[l(u,v)]$	Capacity of the link l
$f[l(u,v)]$	Flow of the link l

The output of the algorithm consists of the selected path $p_s \in P$ for which the flow f is maximized. The selected path includes a starting point (e.g. a terminal in the congested region), an ending point (e.g. a BS), and the links that create the full path from the starting to the ending point (each link is identified by a starting point and ending point each of which is an intermediate node).

2.7.2.2 Selection of nodes through a fitness value evaluation

The input of the algorithm consists of the set of candidate nodes which are located in a specific service area that have ON capabilities (i.e., they have the ability to participate in an ON) and they are legitimate to participate in an ON according to the operator policies, in order to stress on the operator-governance during the ON formation.

The algorithm procedure is given by the pseudo-code that follows:

Algorithm 7: Selection of nodes through a fitness value evaluation

```

1. Retrieve candidate node's  $i$  fitness value  $fv_i$  based on the following formula:
   
$$fv_i = x_i * [ (e_i * w_e) + (a_i * w_a) + (d_i * w_d) ]$$

2. Evaluate fitness value  $fv_i$ , according to a specified (by the decision maker-operator) threshold
3. if  $fv_i > threshold \{$ 
  Add node  $i$  to the set of accepted nodes
   $\}$ 
  else
    Reject node  $i$ 
   $\}$ 

```

where

v_{ai}	Value of availability (e.g. percentage of the available buffer/cache)
e_i, a_i, d_i	Energy (e.g. percentage of available battery), availability (e.g. percentage of available buffer/cache) and delivery probability (e.g. ratio of successfully transmitted packets to packets received by a node) attributes of node i
w_e, w_a, w_d	Weights for energy, availability and delivery probability attributes

$$w_e + w_a + w_d = 1 \quad (32)$$

$$x_i = \begin{cases} 1, & e_i > 0 \wedge a_i > 0 \\ 0, & e_i = 0 \vee a_i = 0 \end{cases} \quad (33)$$

$$a_i = \begin{cases} 0, & \text{node } i \text{ does not have available interfaces or does not support requested appli-} \\ & \text{cation or does not support ON, or does not have available buffer/ cache} \\ v_{ai} > 0, & \text{otherwise} \end{cases} \quad (34)$$

The output of the algorithm consists of the selected nodes that will form the ON. Then, the ON creation procedure is triggered in order to allow the nodes/terminals to negotiate between each other and establish links.

2.7.3 Integration in OneFIT architecture

Figure 17 provides a mapping of the functionalities of the capacity extension through neighboring terminals algorithm to the OneFIT functional architecture and the functionalities entities as defined in D2.2 [3]. Also, Figure 18 provides the mapping of the functionalities of the selection of nodes through a fitness value evaluation to the OneFIT functional entities.

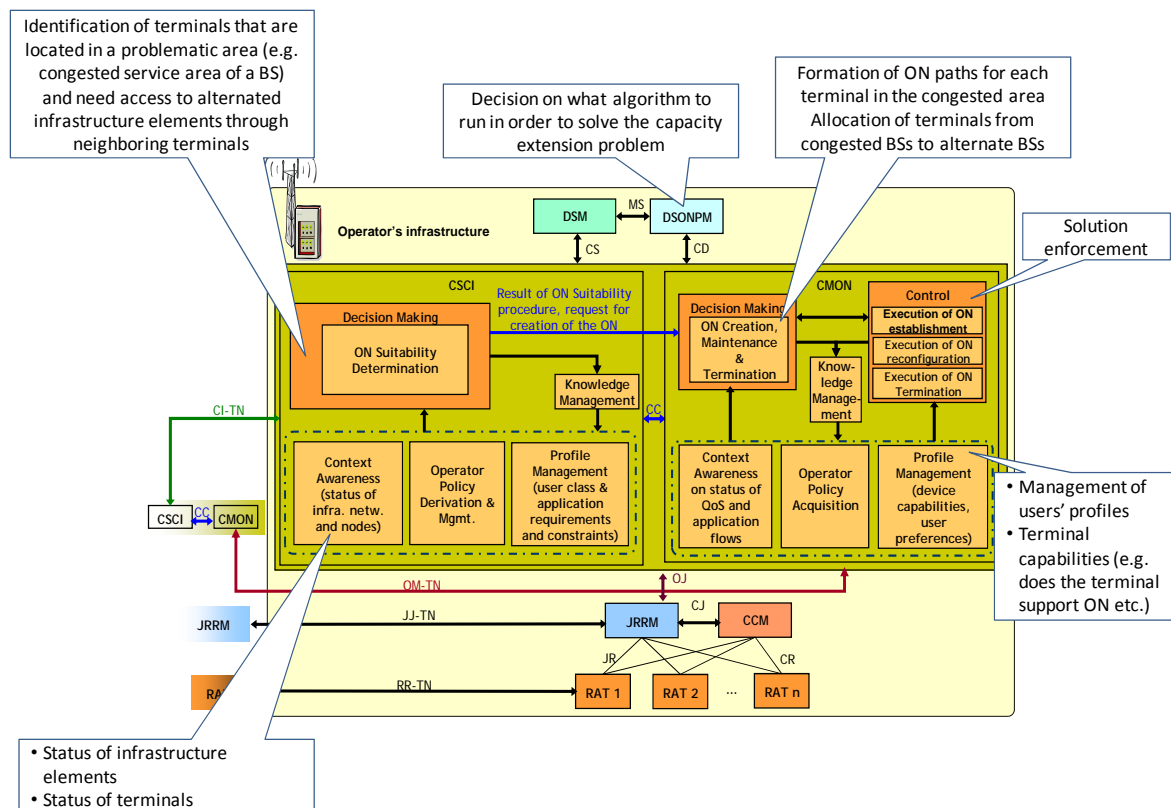


Figure 17 : Mapping of the capacity extension through neighboring terminals concept to the OneFIT functional architecture

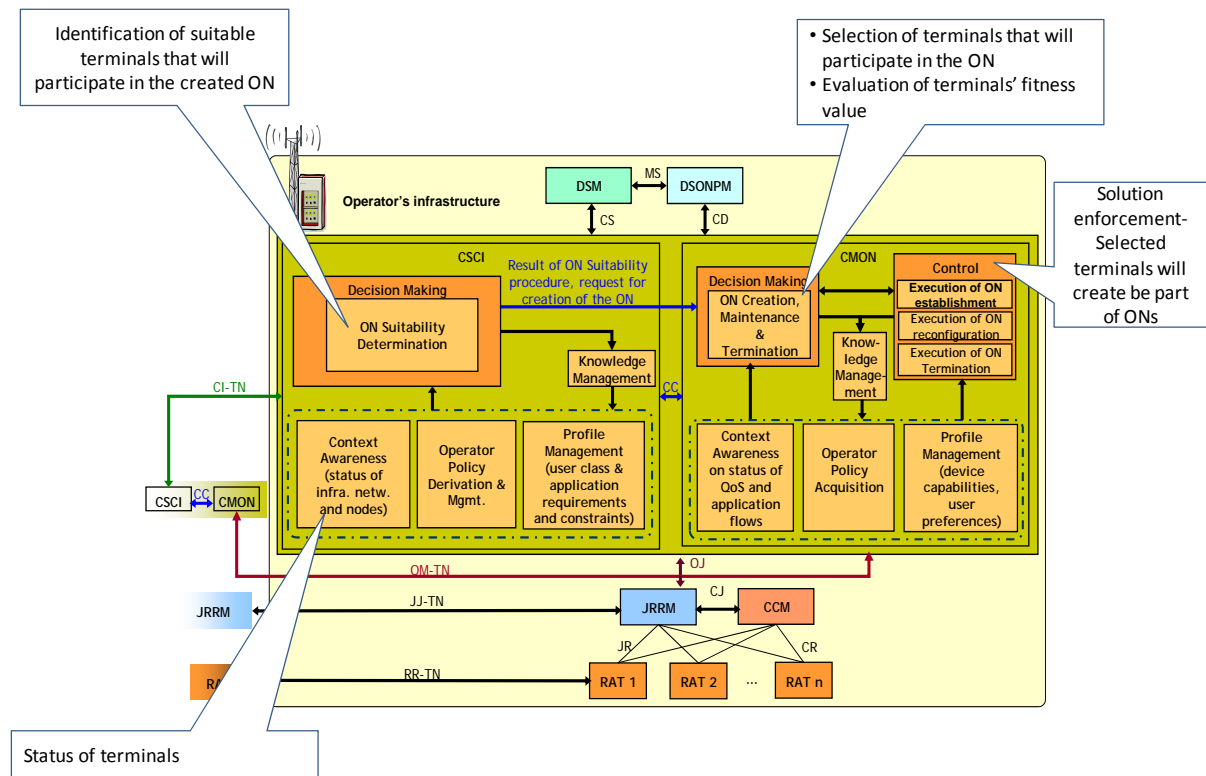


Figure 18 : Mapping of the selection of nodes through a fitness value evaluation concept to the OneFIT functional architecture

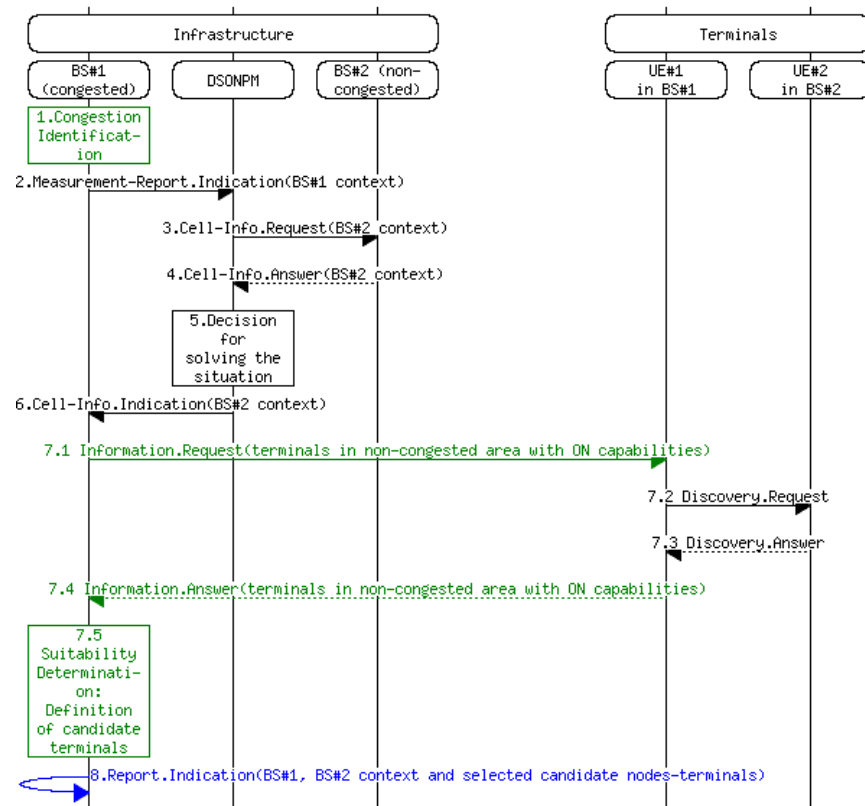


Figure 19: Message Sequence Chart for the capacity extension through neighboring terminals scenario (suitability determination)

The procedure can be supported by means of the C4MS messages that have been defined in D3.3 [7]. In particular, Figure 19 and Figure 20 illustrate the associated message sequence chart for the capacity extension through neighboring terminals scenario, while Figure 21 provides a message sequence chart in order to show how the selection of nodes through a fitness value evaluation in order to provide coverage extension is performed.

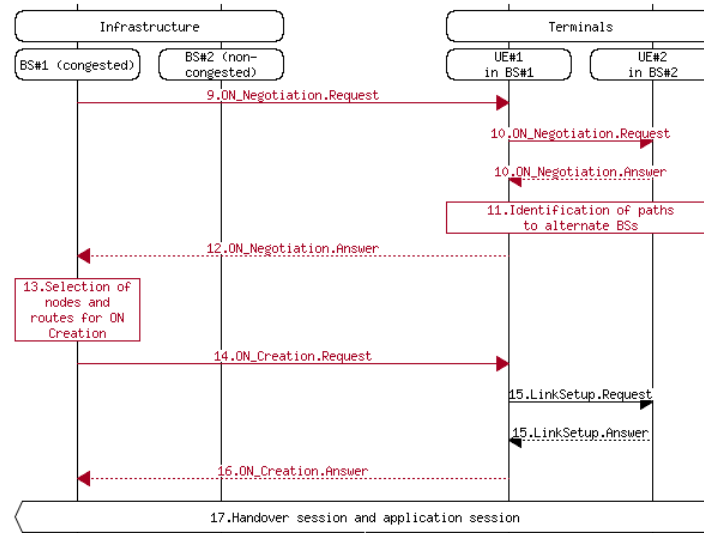


Figure 20: Message Sequence Chart for the capacity extension through neighboring terminals scenario (creation)

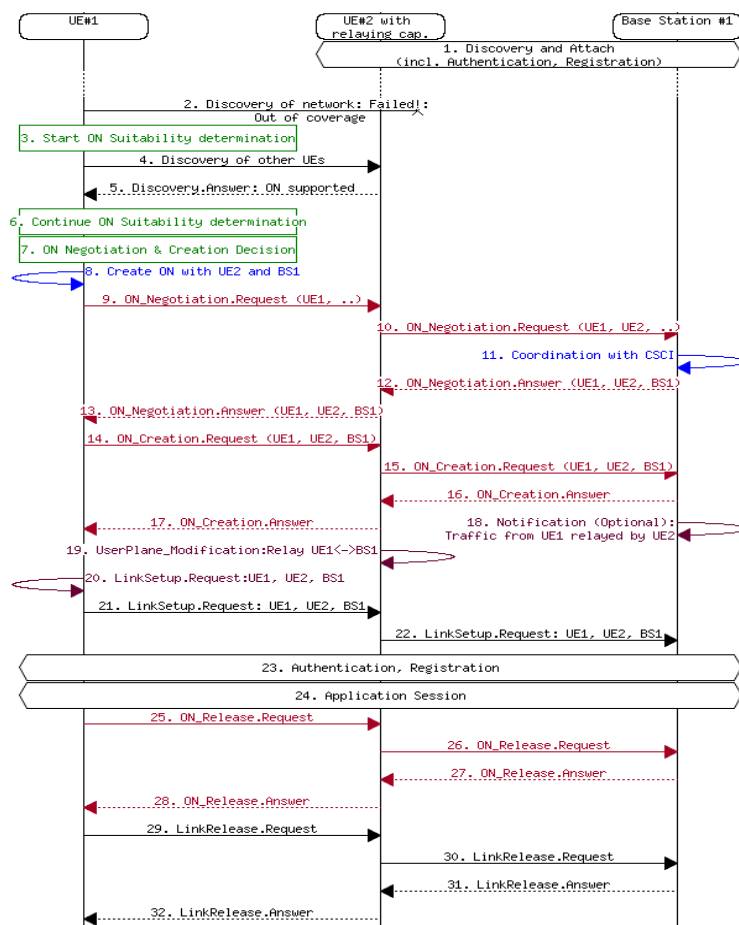


Figure 21: Message Sequence Chart for the selection of nodes through a fitness value evaluation in order to provide coverage extension

2.8 Route pattern selection in ad hoc network

2.8.1 Problem formulation and algorithm concept

The algorithm focuses mainly on the Suitability Determination and Maintenance as the technical challenges as they have been analyzed during WP2. The OneFIT network supporting ad hoc configuration is operator governed.

The diversity of user applications implies different constraints for data transfer in order to guarantee the QoS. In an opportunistic network composed of heterogeneous equipments having different characteristics, it is necessary to take into account the specificities of these equipments and the characteristics of the supported radio access technologies to determine the way to transmit and to receive data. Depending on the service requested, the routing behaviour shall be adapted, and the routing protocol shall consider particular metrics.

2.8.2 Algorithm specification

The proposed algorithm is an enhancement of the routing protocols to take into account the constraints associated to user applications, by selecting appropriate metrics for each service class and to compute these metrics in order to determine the most adapted route to exchange data.

The route pattern selection algorithm acts as a cognitive router to determine the most adapted route to reach the destination in an ad-hoc opportunistic network. The algorithm is able to change the selected pattern depending to the end user application requesting data to transmit. The algorithm determines the set of patterns to be used.

It manages 4 different service classes:

- Conversational class
- Streaming class
- Interactive class
- Background class

It gets also a particular behaviour for the transmission of the control and signalling information.

The algorithm selects the distance (number of hops to reach the destination), to determine the best route for the transmission of control and signalling packets (Figure 22). This pattern applies also for C4MS messages.

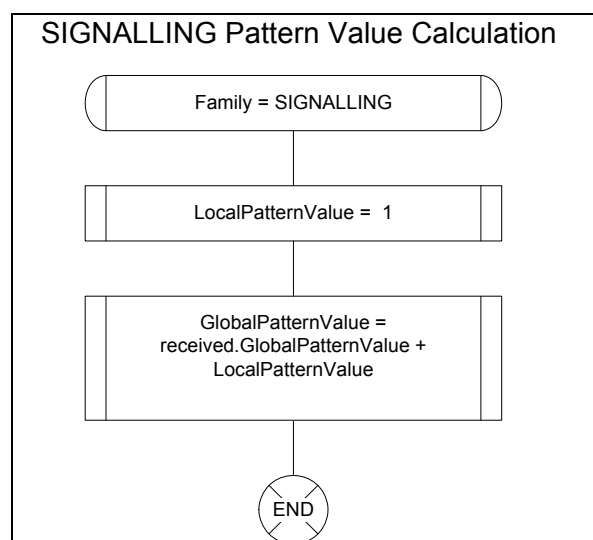
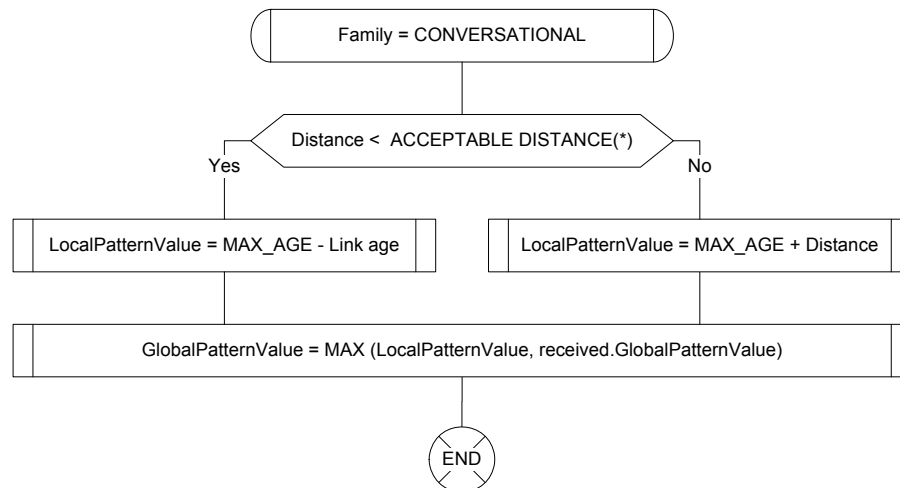


Figure 22 : Flow chart for signalling packet route selection

To transmit user packets related to conversational application, the algorithm selects the route depending on the distance (number of hops), because the distance introduces a certain latency. The second pattern used to determine the most adapted route is the age of the considered route in order to use the most stable routes (Figure 23).

CONVERSATIONAL Pattern Value Calculation



(*) distance represents a certain latency

Figure 23 : Flow chart for conversational packet route selection

To transmit user packets related to streaming application, the algorithm selects the route depending on the available throughput, and it uses also as the link quality as secondary pattern (Figure 24). The available throughput is calculated by for all the possible routes connected to reach the destination.

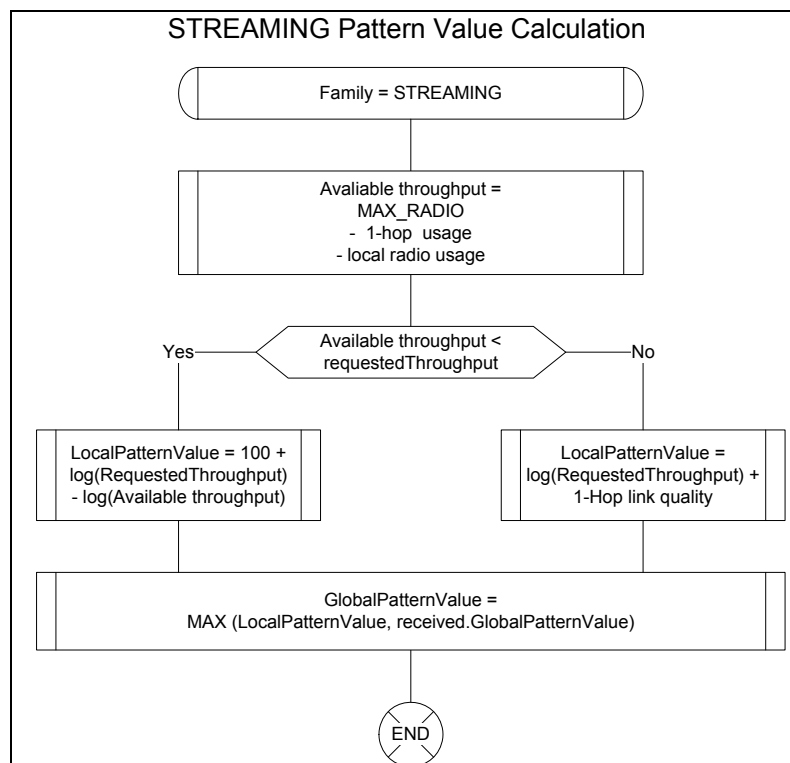


Figure 24 : Flow chart for streaming packet route selection

The background class applications are usually identified to use a “best effort” mechanism. The algorithm uses only the pattern distance (as for the signalling and control packet) to determine the most adapted route (Figure 25).

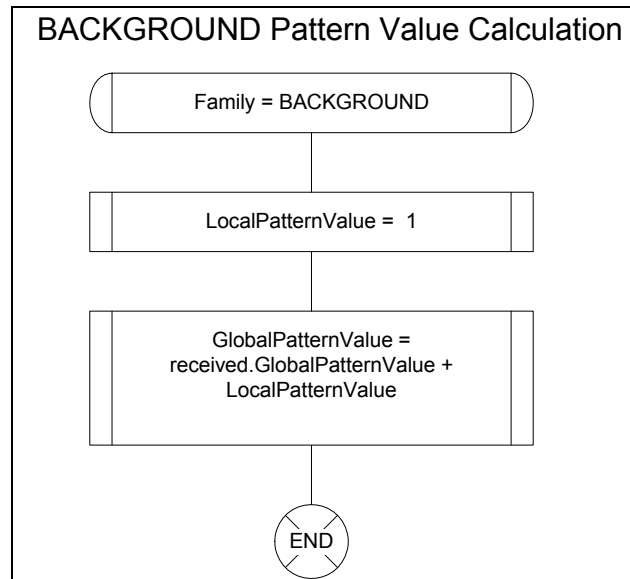


Figure 25 : Flow chart for background packet route selection

2.8.3 Integration in OneFIT architecture

The route pattern selection algorithm has to be seen as a functional module integrated in the both CSCI and CMON. The purpose of the algorithm is to be triggered any time a packet has to be transmitted over the air, to be able to establish and to select the most adapted route to transfer the data to the destination (i.e. to reach the infrastructure).

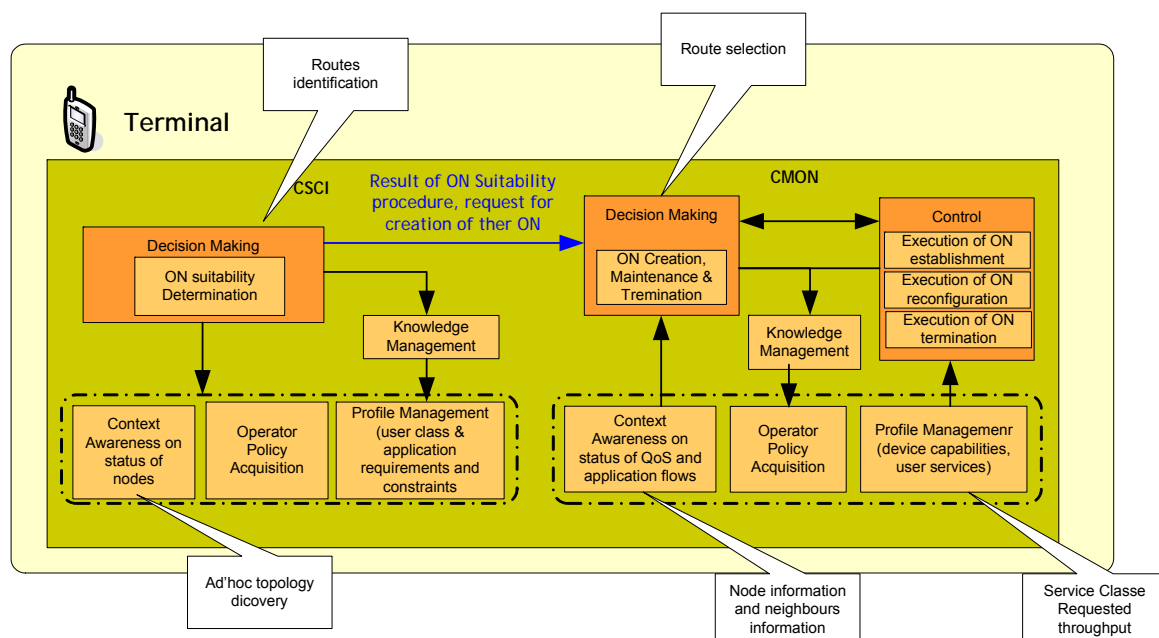


Figure 26 : Mapping of the route selection algorithm in the OneFIT functional architecture

During the ON suitability determination stage, it participates to the discovery of the topological environment, of each node involved in the opportunistic network. The figure below depicts precisely the moment of the algorithm processing during the ON suitability determination stage.

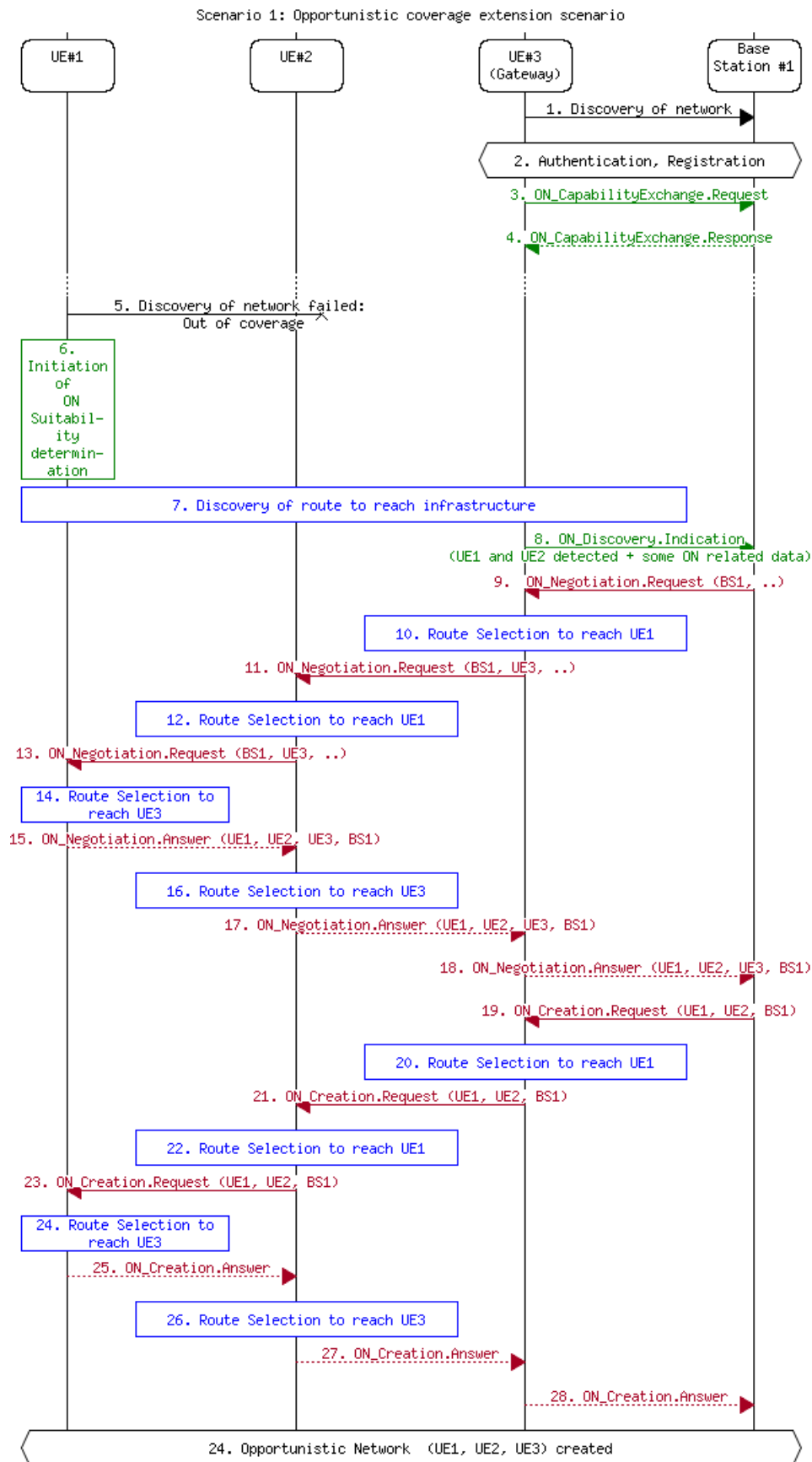


Figure 27: Sequence Diagram for Route pattern selection algorithm during ON Suitability determination

During the ON maintenance stage, the algorithm is applied for each packet of user data to be transmitted over the air, and according to the type of application (i.e.: the DSCP field located into the IP frame header), it determines, which route is allowed to be activated in order to satisfy the QoS related to the application. The algorithm requires also information about the context of the nodes and the context of its neighbours provided by the C4MS messages to apply its decision rules.

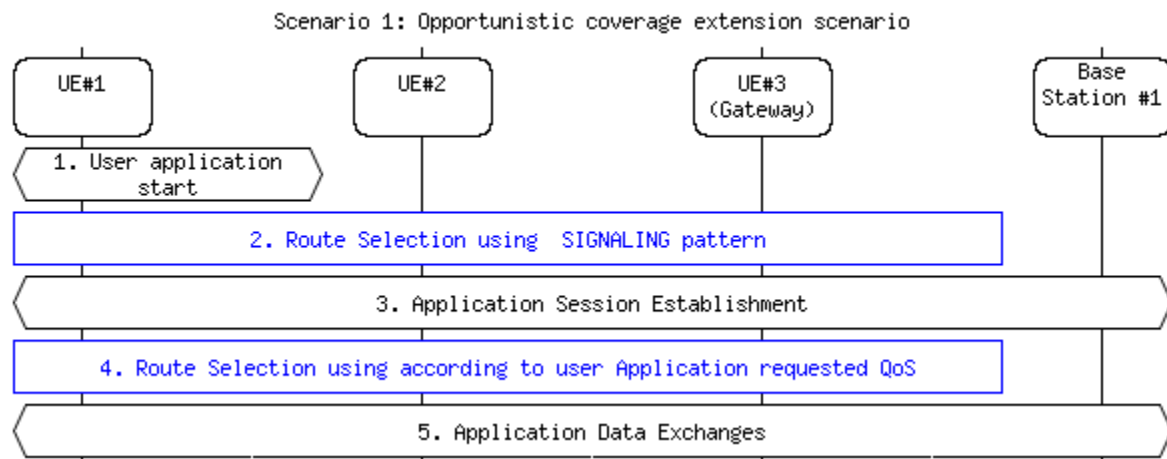


Figure 28: Sequence Diagram for Route pattern selection algorithm during ON maintenance

2.9 Multi-flow routes co-determination

2.9.1 Problem formulation and algorithm concept

The class of Mobile Ad-Hoc Network (MANET) is particularly prominent in Private Mobile Radios networks management, as these networks have to be deployable in harsh environments, with infrastructure-less dependency.

The main characteristics of these networks are the self neighbourhood detection and routing paths creation and the dynamic management of links/nodes.

The issues to be raised in terms of routing enhancement are manifold. One of these issues is the Quality of Service management, and in particular the routing based throughput optimization including resource allocation optimization. Algorithms have been proposed to optimize routing protocols for MANETs. Extensions integrate to these protocols a quality of service management.

In [46] is proposed a multi-flow routes co-determination algorithm, in addition to these optimizations. This algorithm combines the (re)routing of traffic flows on ad-hoc network with a throughput optimization technique called network coding. We present in the following simulation results on the multi-flow routes co-determination, and on extensions to initial and terminal delegated nodes to extend the topology situations the algorithm may be applied to.

2.9.1.1 Network coding principles

The concept of *network coding* was first introduced for satellite communication networks in [47] and then fully developed in [48].

The principle of network coding is described in Figure 29, applied on the butterfly topology. This figure presents two traffic flows, one from S_1 to D and F, the other one from S_2 to D and F. Moreover each one of the common egress node may receive from one path one of the traffic flow, and from one part of one another path (which may be restricted to only one node), the two traffics are relayed using the same relaying nodes resource. The principle is to code the two traffic flows with a common smaller one, using a coding function $Nc()$, the traffic flow relevant from this flow being decoded by the use of the other flows already received. In the example the coding function is the

bitstream *xor* of the two flows (considered of numbered packets of the same size). In D(resp.F), receiving X_1 (resp. X_2) and X_1 or X_2 , it easily deduces X_2 (resp. X_1).

The following figure shows the differences between the use of network coding and a classical independent flow route allocation. The gain in terms of throughput and number of messages sent between the two alternatives is of $1/3$ (from 6 emission to 4), with means also a gain in radio resources and in power consumption in the relay nodes. In particular in the first situation the node E receives two packets and sends two packets (and causes a bottleneck in the flows, impacting the QoS) whereas in the second one, it receives and sends only one packet (with a more homogeneous traffic load between the nodes in the topology).

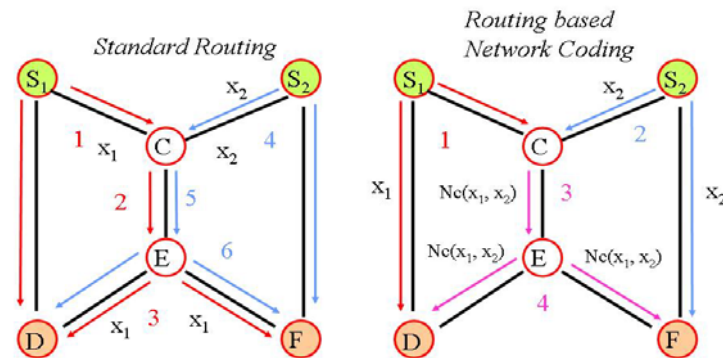


Figure 29: Network coding principle from the butterfly topology

Figure 30 presents the application of the network coding optimization on a 2 opposite sides flow relay topology. The optimization in terms of throughput is of $N/(2N+2)$ [13], with N as the number of relay nodes. The examples provided present network 2 inter-flows coding optimizations. The principles presented in this paper may be extended to n -flows optimization, with $Nc()$ defined as a linear combination of n flows.

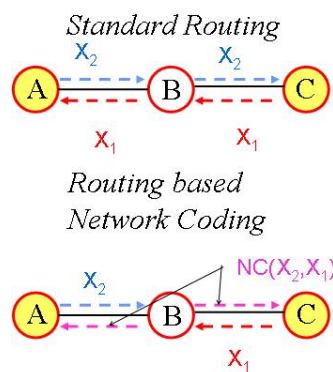


Figure 30: Network coding principle from the 2 sides flows relay topology

2.9.1.2 Mapping to OneFIT scenarios/use cases

As for the Route pattern selection in mesh network section, the algorithm is related to the optimization of the communication of the ad-hoc part of the opportunistic network:

- Scenario 1 : Opportunistic coverage extension,
- Scenario 2 : Opportunistic capacity extension and
- Scenario 3: Infrastructure supported opportunistic ad-hoc networking.

2.9.1.3 Mapping to ON Lifecycle

This algorithm is specific to the best route determination on an ad-hoc network the topology has already been set. This algorithm is dedicated to the maintenance phase.

2.9.2 Algorithm specification

The multi flow route co-determination algorithm aims at completing routing algorithm in the flooding and information recovery phases from the egress nodes of flows to be established. The detailed description of the algorithm may be found in [46].

2.9.2.1 Flooding phase

In a first step, during the flooding phase of the flow route establishment, the following information is stored on the nodes crossed. For each flow, this includes the distance in number of steps to the initial node, and the precedent node in the path. The links are considered as bidirectional and stable during the traffic establishment. In the following figure are presented the results of this phase on a S1 to D and F for the flow X1, and the S2 to D and F for the flow X2. A simple bounded Dijkstra algorithm may be used to implement this phase. This phase may be applied at traffic setup, or by polling after traffic establishment to optimize the global traffic workload with new independent flows establishment.

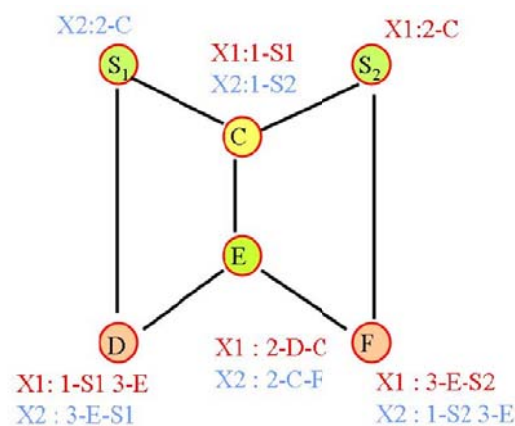


Figure 31: Information memorized during the flooding phase

2.9.2.2 Information recovery phase

In a second step the egress nodes send information to the ingress nodes to create the flow routes, catching in the relay nodes the information needed to define at the ingress node level if a network coding optimization with one other flow is applicable.

This step consists to send information on these flows, periodically from candidate egress nodes by sending specific messages. These messages, called Mtopo messages contain (1) the list of the nodes of the path of relay nodes from egress to ingress nodes, (2) if one of these relay nodes was the initial node of flows (for S_1 – resp. S_2 – to have the knowledge of the path $S_2 \rightarrow F$ – resp $S_1 \rightarrow D$ – for the traffic X_2 – resp. X_1 –), (3) if two flows are bidirectional (as in Figure 32).

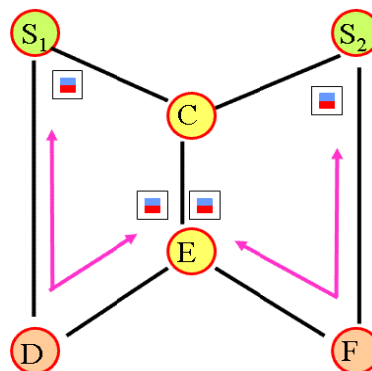


Figure 32: Mtopo messages sent to initial nodes

2.9.2.3 Flow path setup phase

This phase consists on identifying the best route to send the flows at the initial node level, from all the M_{topo} messages received. The information of these messages contains in particular the information needed to know the traffics from other flows, to identify pivot nodes (which initiates and relay the network coding of flows), and if these pivot nodes are bidirectional.

In the flows initialization, the establishment messages set-up the paths to transmit the flows, and inform relay nodes of these path network coding is applied, identifying bidirectional ones, on which memorization, coding and decoding phases are applied. For example in Figure 30 the node B has to memorize packets from A and C, and to apply coding of these packets to send them, A and C have to memorize the packets sent, to decode the coded packets from B.

2.9.2.4 Delegated nodes optimization

In the algorithm proposed in the previous section, we restrained the identification of initial nodes as the nodes initiating two flows or nodes initial of a flow and terminal of one another. In the same way, destination nodes candidates are nodes terminal of two flows and nodes initial of a flow and terminal of one another.

From a practical analysis of the topologies the algorithm may be applied to, it appears some topologies are very close to “canonical” ones and can’t be candidate for network coding optimization although such optimization could be applied. For example the topologies and flows depicted in Figure 33 shows a potential use of network coding optimization, but needs adaptations to extend the set of candidate topologies. We propose to extend the set of the topologies with the definition of delegated nodes, on which the initial and final nodes may delegate to nodes which respect the initial and terminal candidate nodes prerequisites to apply the network coding optimization. As a first definition of delegated nodes, we define as potential candidates the unique neighbour node of the initial and terminal nodes of a traffic (as S_{21} and F_1 in the example of Figure 33).

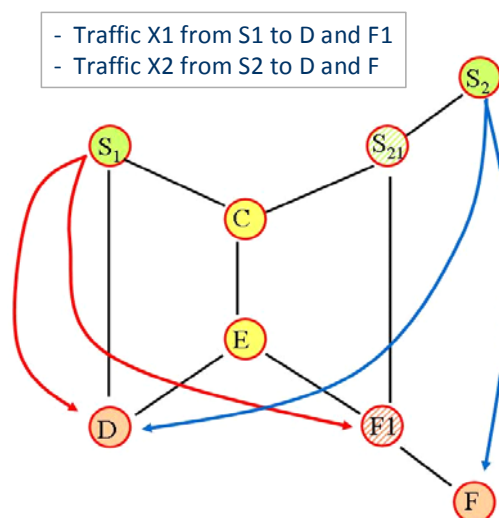


Figure 33: Network coding optimization with delegated nodes extension

2.9.3 Integration in OneFIT architecture

The algorithm is located in the CMON module (see Figure 34). It is a distributed algorithm located on each terminal (see Figure 35). It runs as a distributed algorithm. It is activated during the ON maintenance procedure.

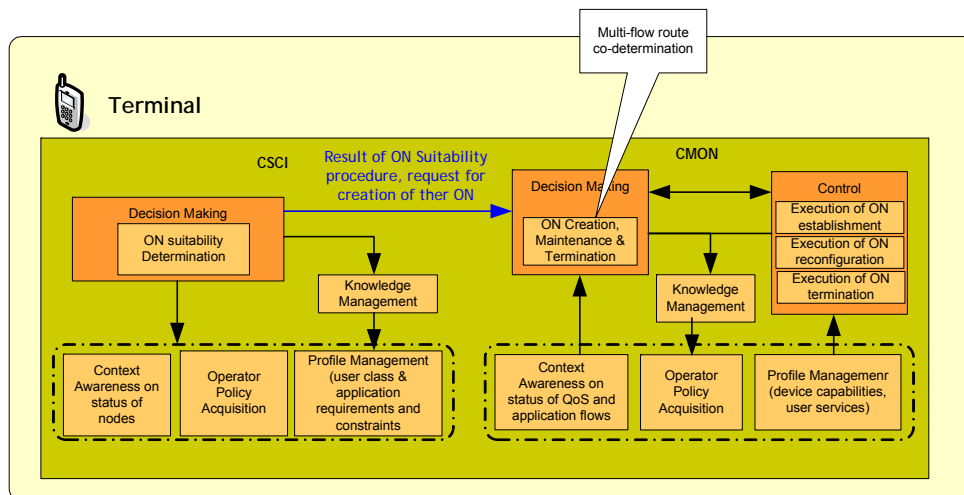


Figure 34: Integration of the algorithm in the functional architecture

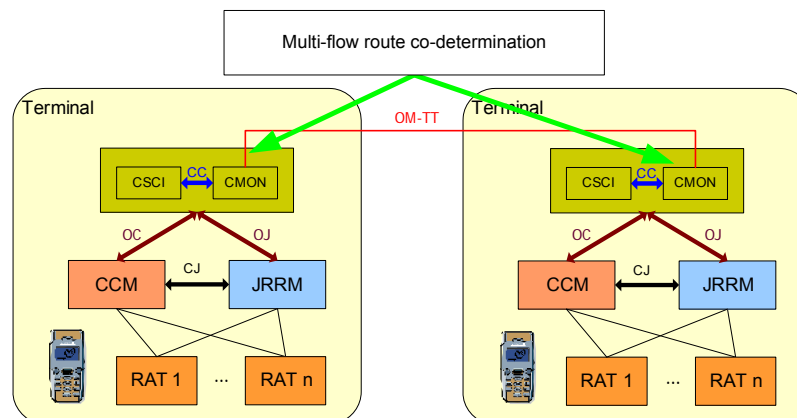


Figure 35: Integration of the algorithm in the functional architecture

2.10 QoS and Spectrum – aware Routing Techniques

2.10.1 Problem formulation and algorithm concept

The proposed routing protocol uses the available channels opportunistically for the purpose of routing data. The algorithm is a spectrum-aware version of OLSR routing protocol which opportunistically forwards the data to destination. It is assumed that ON nodes are equipped with 802.11 wireless cards and can utilize all available ISM band channels to communicate with each other. It is also assumed that there is a central entity e.g. at BS, which receives updates on route and channel availabilities from the ON nodes and continuously finds the shortest paths between all pair of nodes considering their channel availabilities.

Route calculation algorithm uses the ETX metric[48] which is based on the predicted number of data transmissions required to send a packet over a link.

The algorithm is not scenario specific.

2.10.2 Algorithm specification

The proposed algorithm is based on Dijkstra's shortest path algorithm. The inputs to the algorithm consist of:

- ON nodes
- ON nodes connectivity (topology)

- Channel (spectrum) availability

Outputs of the algorithm:

- Best quality route: selected route supports the highest possible throughput (based on ETX metric) and is calculated based on channel availabilities of each ON node [on per hop/link].

2.10.2.1 Overview of OLSR

OLSR native HELLO messages are used to decide on candidates to be set as MPRs (Multi Point Relays) to forward the data whilst TC (Topology Control) messages inform all nodes of the connectivity of nodes through the MPRs. Furthermore Multiple Interface Declaration (MID) messages of OLSR are used to update the channel usage/status within the network.

When a node uses a channel for transmission, it periodically broadcasts MID messages to inform all of the one-hop neighbours that the channel is occupied. When a Primary User (PU) starts using a channel, all the one-hop and two-hop neighbours of a node should be informed of the occupied channel to avoid interference with primaries (via MID messages).

At line number 2 of the algorithm, one of the nodes is chosen out of the available set of vertices as source denoted as “s”. At line 3 and 4 the parameters of the algorithm is initialized for every vertex that have not been traversed (at this stage it would be every vertex except the source). The main loop starts at line 8 and ends at line 27 which iterates as long as the vertex set of the graph is not zero. Another inner loop starts at line 14 that iterates based on the number of neighbours that source node “s” has in its vicinity. For every neighbours of the source node “s” another loop which starts at line 16 checks the number of channels available between node “s” and that specific neighbour. The numbers of channels available to a node are acquired through the DSM unit of the infrastructure. If a channel is used by another ON node or for some reason it is not available in the vicinity of that node, it is the infrastructure that updates the algorithm with the up to date information on that channel. The iteration of the innermost loop to the outermost loop computes the best set of routes among each pair of ON nodes which supports highest throughput.

Algorithm 8: Spectrum-aware Route Calculation Algorithm

```

1.  Start Spectrum_aware_shortest_path_algorithm
2.  for each vertex s in Graph;
3.      totalCurrBenef[s] := infinity ;
4.      previous[s] := undefined ;
5.  end for ;
6.  totalCurrBenef[source] := 0 ;
7.  G := the set of all nodes in Graph ;
8.  while G is not empty:
9.      d := vertex in G with smallest distance in totalCurrBenef[] ;
10.     if totalCurrBenef[u] = infinity:
11.         break ;
12.     end if ;
13.     remove d from G ;
14.     for each neighbor s of d:
15.         noChannelssu = getNoChannels_between(s,d);
16.         while noChannelssd > 0:
17.             currETX = oneByonechannelsd.getETX;
18.             ETXBenef := totalCurrBenef[d] + currETX;
19.             if ETXBenef < totalCurrBenef[s]:

```

```

20.         totalCurrBenef[s] := ETXBenef ;
21.     end if ;
22.     decrease noChannelssd;
23.     end while;
24.     previous[s] := d ;
25.     decrease-key s in G;    // Consider s as processed and iterate the loop
26. end for ;
27. end while ;
28. return totalCurrBenef[] ;
29. end Spectrum_aware_shortest_path_algorithm

```

2.10.3 Integration in OneFIT architecture

2.10.3.1 Mapping to CMON and CSCI

As shown in Figure 36, the algorithm sits in decision making block of CMON to decide on best spectrum aware path for routing the data.

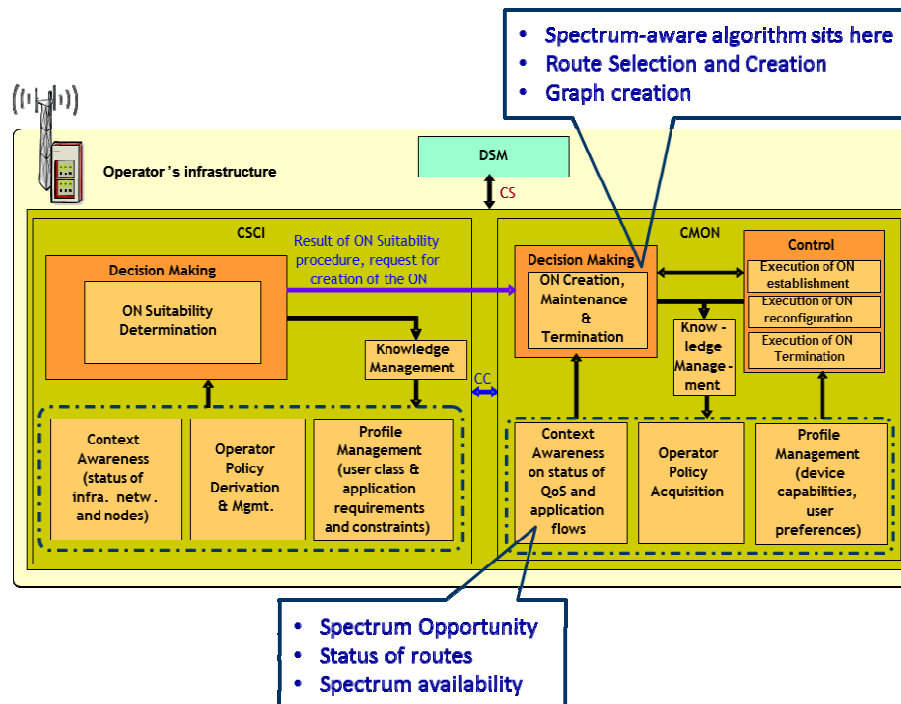


Figure 36: Mapping of QoS and Spectrum aware routing algorithm to CSCI and CMON

2.10.3.2 Mapping to C4MS signalling

As shown in Figure 37 after UE#1 initiates the Request message to establish a link to UE#2, the usual signalling happens between BS and DSM modules to check the spectrum availability. Here is where our algorithm runs the “spectrum aware route selection” to find the most efficient route selection. Then C4MS signalling messages respond back from BS to UE#1 and UE#2 to allocate the spectrum bands. After the spectrum is allocated, OLSR routing protocol running at step 12 routes the data between UE#1 and UE#2 and the connection is fully established. Since the routing algorithm is occupying the spectrum band, at step 14 BS should respond back to DSM regarding the busy band and hence that band wouldn’t be used by other UEs until the data transmission is finished.

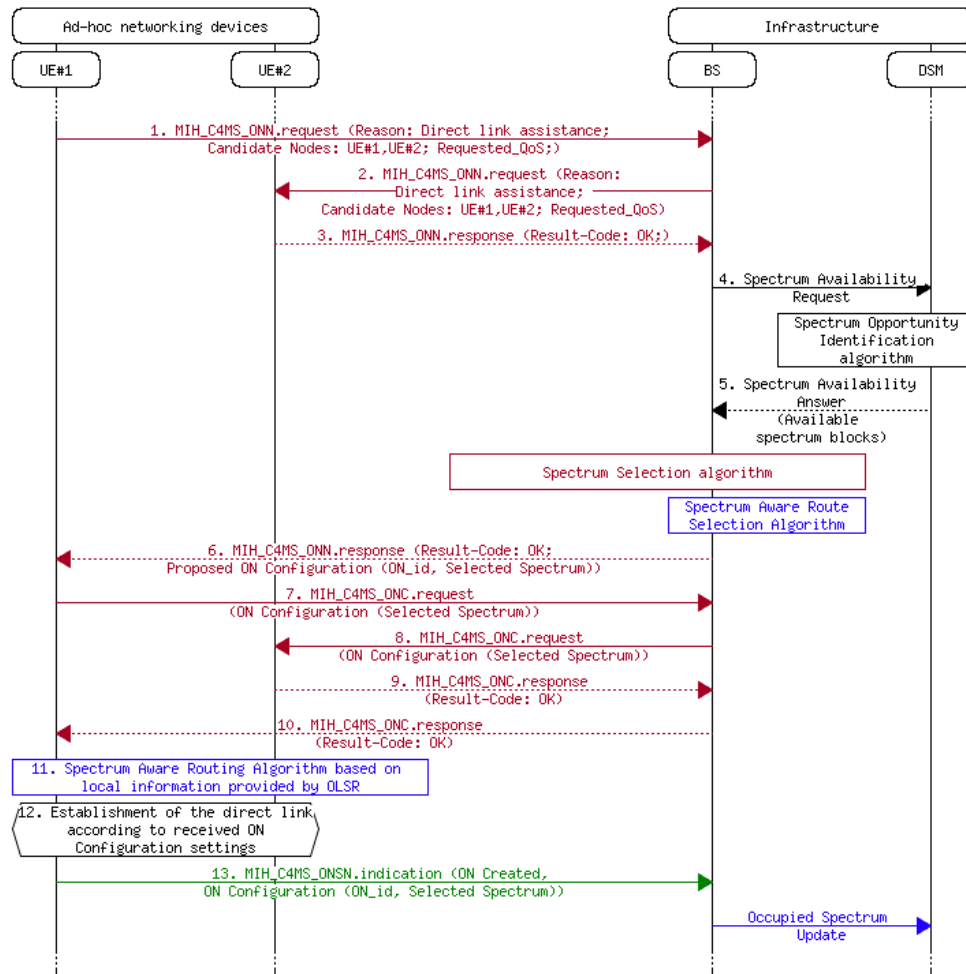


Figure 37: Spectrum Aware Route Selection Algorithm mapping in C4MS Signalling

2.11 Techniques for Network Reconfiguration – topology Design

2.11.1 Problem formulation and algorithm concept

The challenge addressed is creation and maintenance of network topology through enabling coordination in decision making among the nodes taking into account impact of various parameters (e.g. Transmission range) to establish links/topology with a set of desired global properties and constraints. The desired properties are:

- K connectivity (for reliability, reduction in rerouting)
- Interference minimization (Capacity improvement)
- Energy efficiency (Reduced power consumption and increased network lifetime)

The topology control can be enabled through scheduling or power control. The topology control through scheduling can further be categorized in node scheduling [26][27] and link scheduling [28]. In node scheduling the redundant nodes or the nodes falling below a threshold (criteria to achieve global property) are removed, while in link scheduling the links formed by each node are analysed. In case of power control the objective is to minimize the power per node which ensures connectivity [29], and power control can be categorized into common power control [30], variable power control (range assignment) [31], high power regime [35] and low power regime [36].

In order to attain the optimal solution for topology control different approaches of Network Optimization Theory can be adopted; for instance convex optimization, linear programming, geometric programming and stochastic programming etc. The optimal scheduling of nodes and links

is addressed in [37], however achieving the optimal minimum power allocation remains an infeasible problem. The optimal solutions (for min. power under SINR physical interference model) so far provided either are applicable to the networks where number of nodes is under six [38] or the suboptimal or approximation approach is adopted [39]. The reason of infeasibility is the non-linear nature of interference constraint (SINR) and the presence of conflicts in power assignments as the number of nodes increases. In order to address this problem, different approximation approaches are used. The column generation approach is one of the latest approximation methods used for optimal power allocation while considering interference [41]. Besides, column generation, recently, the interference is mapped as knapsack optimization problem in [42] however, [42] attempts to achieve optimal scheduling instead of optimal power allocation. In [37] the optimal power allocation is provided under k-connectivity and flow constraints but the interference is not taken into account.

Thus, among the optimal solutions, approximation approaches and other practical methods such as graph theory, prediction and learning methods and evolutionary algorithms [42], the full set of constraints namely: k-connectivity, interference handling and energy efficiency have not been explicitly addressed simultaneously. The proposed algorithm intends to capture under a single formulation the requirements on k-connectivity, interference management and energy efficiency.

The design and implementation of the proposed TC algorithmic approach is divided into a number of phases.

First phase:

- The centralized design: through Mixed Integer Linear Programming providing the optimal solution (min. TX power per node values) under k-connectivity, energy and maximum power constraints; includes continuous, discrete and incremental power values.

Second phase:

- Introduction of “interference” constraint into main MILP formulation
- Development of the distributed/localized version of algorithm (based on approximation techniques or heuristics)

Third phase:

- Porting/Implementation of algorithm on OMNET++ platform and performance evaluations

2.11.2 Algorithm specification

Inputs: no. of nodes, number of commodities [pre-calculated], demand per commodity [= k value], k value, position of the node [inter-node distances used to calculate path loss], max. power level per node.

Outputs: min. required power level per node to maintain given k.

2.11.2.1 Algorithmic Procedures

PHASE i

Continuous formulation

The formulation done as Mixed Integer Linear Programming taking into account constraints such as, flow control, maximum allocated power and path loss between the nodes. The K connectivity here refers to the K Vertex connectivity; here it is implemented by allowing each node to connect to at least k other nodes. Thus, it ensures that even after removing K-1 nodes, network will still be connected. A set of commodities are taken into account (number of commodities can be varied), each with K demand from a particular source to destination. Although currently there are no maximum hop count constraints, it can be added as it is an independent constraint. The MILP formulation is as follow: where V is the set of nodes/terminals, C is the set of all commodities having its origin as $o(c)$ and destination denoted as $d(c)$. P_i is the power allocation variable for each node i . And $f_{i,j}^c$ is the flow variable which tends to be one if edge (i, j) is used for commodity c .

Objective Function:

$$\min \sum_i P_i \quad (35)$$

Subject to:

->Topology constraints:

$$P_i \geq w(i,j)X_{ij} \quad \forall i,j \in V \quad (36)$$

$$P_i \geq w(i,j)X_{ji} \quad \forall i,j \in V$$

$$(37)$$

$$P_i \geq 0 \quad \forall i \in V \quad (38)$$

-> K connectivity constraints

$$\sum_i X_{ij} \geq k - 1 \quad \forall i,j \in V \quad (39)$$

$$P_i \geq P_i^k \quad \forall i \in V \quad (40)$$

-> Flow constraints:

$$\sum_i f_{i,j}^c - \sum_i f_{j,i}^c = D_c(i) \quad \forall i,j \in V, c \in C \quad (41)$$

$$\sum_i f_{i,j}^c \leq 1 \quad \forall i \neq o(c), j \neq d(c), i \in V, c \in C \quad (42)$$

$$f_{i,j}^c \in \{0,1\} \quad \forall i,j \in V, c \in C \quad (43)$$

Discrete formulation

The second set of formulation i.e. discrete power model orDP has been implemented with K connectivity and flow constraints. This formulation takes discrete levels of powers per node and remains valid even in the heterogeneous environment that means the maximum power of nodes and number of power levels available per node may different. Here, $P_i = [p_1, p_2 \dots p_{\varphi(i)}]$ such that $l = 1 \dots \varphi(i)$ and $\varphi(i) \leq V$. While $\overline{l(i)}$ is the level of power essential for reaching k nodes, and $l(i',j)$ is the power level needed to enable edge (i,j) $i,j \in V$.

Objective Function:

$$\min \sum_{i \in V} \sum_{l=1}^{\varphi(i)} p_i^l \cdot w_i^l \quad (44)$$

Subject to:

$$\sum_i f_{i,j}^c - \sum_i f_{j,i}^c = D_c(i) \quad \forall i,j \in V, c \in C \quad (45)$$

$$\sum_i f_{i,j}^c \leq 1 \quad \forall i \neq o(c), j \neq d(c), i \in V, c \in C \quad (46)$$

$$\sum_{l=\overline{l(i)}}^{\varphi(i)} w_i^l = 1 \quad \forall i \in V \quad (47)$$

$$w_i^l = 0 \quad \forall i \in V, l = 1 \dots \overline{l(i)} - 1 \quad (48)$$

$$\sum_{l=\max(\overline{l(i)}, l(i',j))}^{\varphi(i)} p_i^l w_i^l \geq e(i,j) f_{i,j}^c \quad \forall i,j \in V, c \in C \quad (49)$$

$$f_{i,j}^c \in \{0,1\} \quad \forall i,j \in V, c \in C \quad (50)$$

$$w_i^l \in \{0,1\} \quad \forall i,j \in V, l = 1 \dots \varphi(i) \quad (51)$$

Incremental formulation

The third set of formulation, the incremental [difference between consecutive power levels] power model (IP), is also kept in linear region, and it performs optimization while considering the difference in power levels. This formulation allows to achieve relatively utilize less power while maintaining the

k connectivity. Along with that the time complexity of the incremental power model is also least of all.

Objective Function:

$$\min \sum_{i \in V} \sum_l^{\varphi(i)} q_i^l \cdot x_i^l \quad (52)$$

Subject to:

$$\sum_i f_{i,j}^c - \sum_i f_{j,i}^c = D_c(i) \quad \forall i, j \in V, c \in C \quad (53)$$

$$\sum_i f_{i,j}^c \leq 1 \quad \forall i \neq o(c), j \neq d(c), i \in V, c \in C \quad (54)$$

$$x_i^l \geq f_{i,j}^c \quad \forall i \in V, c \in C, j \in T_i^l, l = 1 \dots \varphi(i) \quad (55)$$

$$x_i^{l+1} \geq x_i^l \quad \forall i \in V, l = 1 \dots \varphi(i) - 1 \quad (56) \quad x_i^l = 1 \quad \forall i \in V, l = 1 \dots \overline{l(i)} \quad (57) \quad f_{i,j}^c \in \{0,1\} \quad \forall i, j \in V, c \in C \quad (58)$$

$$x_i^l \in \{0,1\} \quad \forall i, j \in V, l = 1 \dots \varphi(i) \quad (59)$$

PHASE ii

In the second phase of the algorithm, where physical SINR is accounted for and the distributed topology control is enabled, a fitness function is defined for each individual node using locally available information only. The pseudo code of the proposed algorithm is:

Algorithm 9: Phase II algorithm overview

Input:

< Direction(θ_i) or Position , Maximum Power p_{imax} , Speed $_i$, SINR $_i$, Residual energy E_i
> for all $i \in N$

Main procedure:

```

-----
While Run time limit doesn't exit
  For all  $i \in N$ 
    Broadcast Hello message <ID, Speed, direction, Maximum power>
    Construct local graph
    Determine interference (SINR) of 2 hop neighbourhood
    Determine Residual Energy of 2 hop neighbourhood
    Determine Speed of 1 hop Neighbourhood
    Calculate value of K for each node by fitness function f
    Adjust the power according to fitness values
    Retain the power until next update interval for stability
  End
End
-----

```

Output:

< Power p_i , , K for each local graph K_i > for all $i \in N$

2.11.3 Integration in OneFIT architecture

Since the first stage of the topology control algorithm for ad hoc networks is based on a centralized approach, it assumes that the complete network information is known [e.g. node positions assumed known to all nodes]. However, in second stage where the algorithm formulation be based on the multi objective optimization function, the algorithm will reside in the node/ terminal level, thus the topology control will be implemented in distributed manner. As, the CMON is the main entity involved in the decision making and control for ON creation, maintenance and termination phases,

it will be the main entity where topology control will reside. CMON-to-CMON communication will be via OM –TT to enable relaying, while OM-TN interface will be used in case of direct BS service. The CSCI will provide CMON with candidate nodes once ON suitability decision has been made by CSCI. The JRRM will provide neighbourhood information (through C4MS) and conditions regarding network for the second stage of distributed topology control.

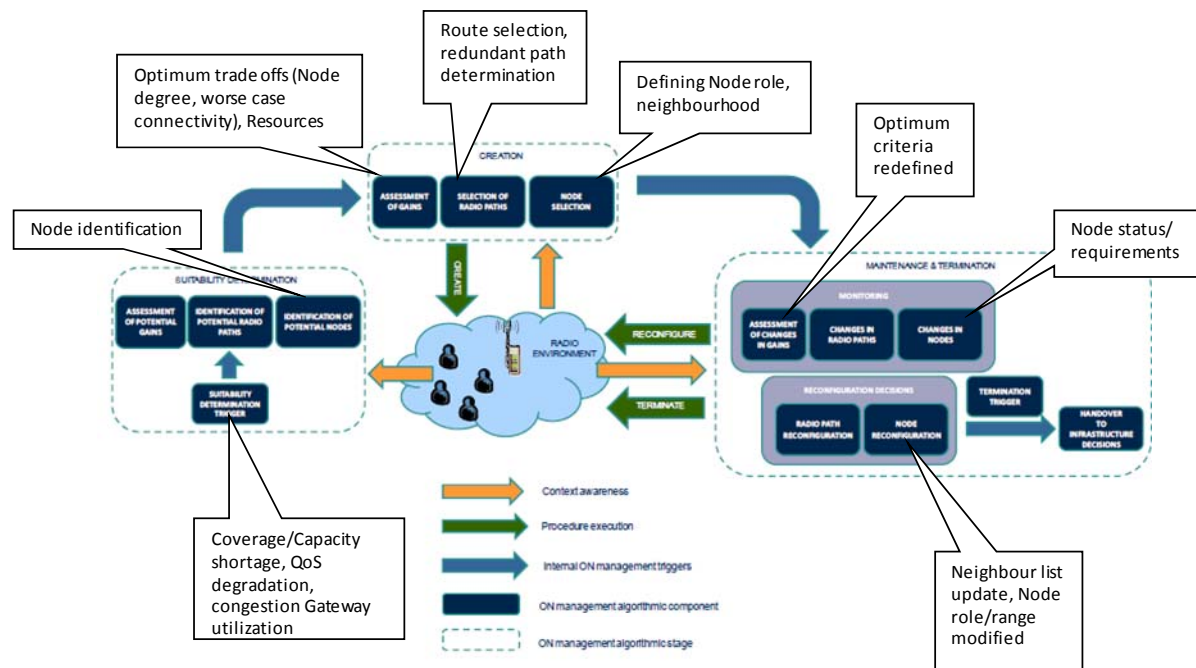


Figure38: Placement of the TC algorithm & components in OneFIT Functional Model

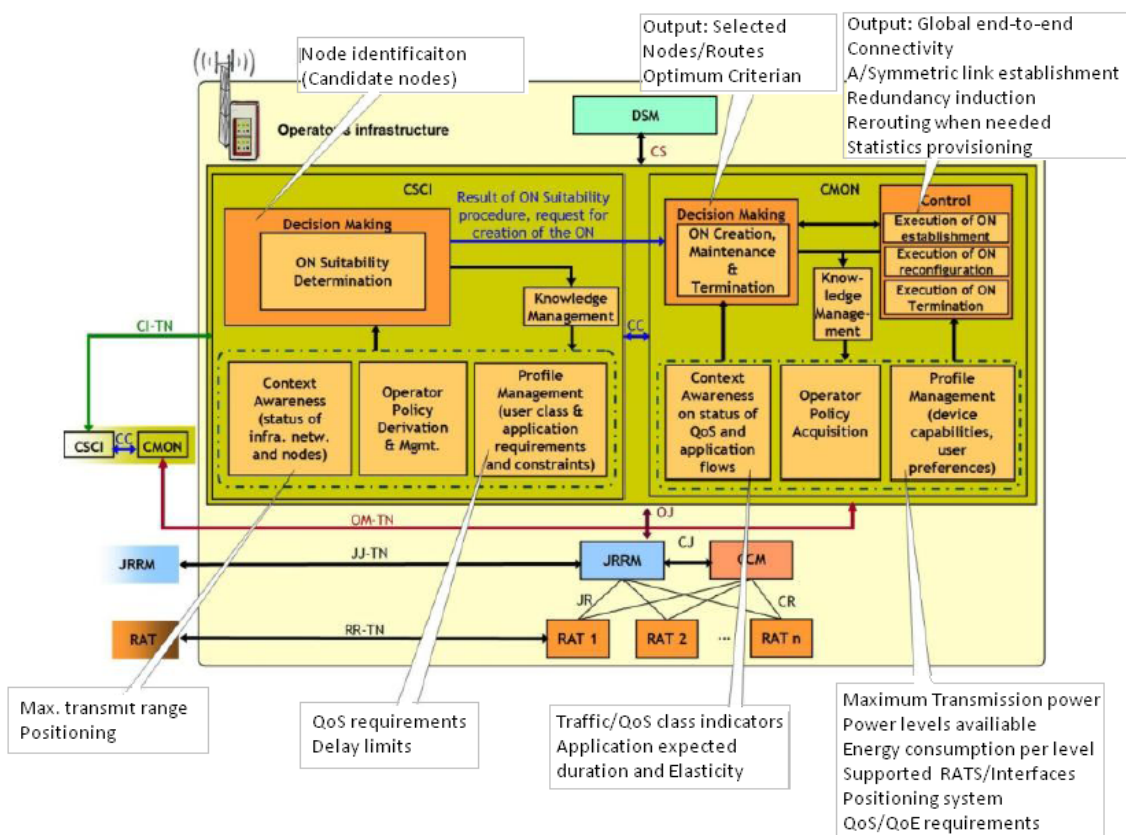


Figure39: Placement of the TC algorithm in OneFIT Functional Architecture

2.12 Application cognitive multi-path routing in wireless mesh networks

2.12.1 Problem formulation and algorithm concept

This algorithm falls into the group of route selection and management algorithms. Its main function is selection and establishment of appropriate set of multiple paths in the wireless backhaul side of the wireless mesh networks (WMNs) in order to opportunistically provide aggregation of the backhaul bandwidth on the access side of the struggling APs. Algorithm takes into account topology of the underlying WMN, backhaul traffic patterns, status of the WMN backhaul links and bandwidth requests at access side of the WMN APs. By providing bandwidth aggregation over multiple backhaul paths, higher levels of backhaul bandwidth utilization and load balancing can be achieved. Algorithm addresses OneFIT Scenario 5. More precisely the use case “Opportunistic backhaul bandwidth aggregation in unlicensed spectrum” is addressed.

The algorithm can be mapped to the following ON lifecycles:

- Suitability determination – checking the validity/feasibility of the multi-path routing as a solution for the problem at hand. Discovery of candidate paths.
- Creation – algorithm will choose appropriate subset of candidate paths and establish them by manipulating routing tables of the underlying single-path routing protocol.
- Maintenance – algorithm will recalculate new multiple paths set if the need for reconfiguration is detected by the WMN monitoring system.
- Termination – when there is no longer a need for backhaul bandwidth aggregation, or multi-path routing imposes more problems (increased interference, packet reordering problems) than benefits, algorithm will terminate the created ON and single path routing protocol will continue to operate regularly.

2.12.2 Algorithm specification

Algorithm for opportunistic multiple backhaul paths selection in WMNs

The algorithm presented in this section makes decision whether or not to create opportunistic network for providing multi-path routing as a solution for the detected problem. Besides having responsibility to decide when to kick in with the multipath routing, the algorithm also selects the multiple paths set which is able to provide required level of bandwidth aggregation. The net effect of opportunistic backhaul bandwidth aggregation is to match the access bandwidth of modern wireless technology with the adequate transport bandwidth in the backhaul/core network. Our proposed solution makes use of OLSR as underlying routing protocol in the WMN. Necessary contextual data is gathered from WMN nodes with Simple Network Management Protocol (SNMP). Decision making algorithm resides on the centralized management server, which monitors network status/state with SNMP protocol and stores gathered contextual data into database. This database contains current and historical contextual data as well as history of previous decision instances.

By inspection of user mobility/migration patterns, traffic flows and application/service mix, a need for increased bandwidth capacity at access side of an AP_i is detected or predicted if similar situations have already been encountered (see Figure 40). Knowledge of reoccurring patterns relative to users mobility, traffic flows and application/service requests, can significantly improve the predictive ability of the management system. The history of contextual data, representing different WMN states and their transitional rules (how WMN goes from one to the other detected state), is of crucial importance for successful pattern recognition and therefore for successful predictions which can improve performance of the decision making process.

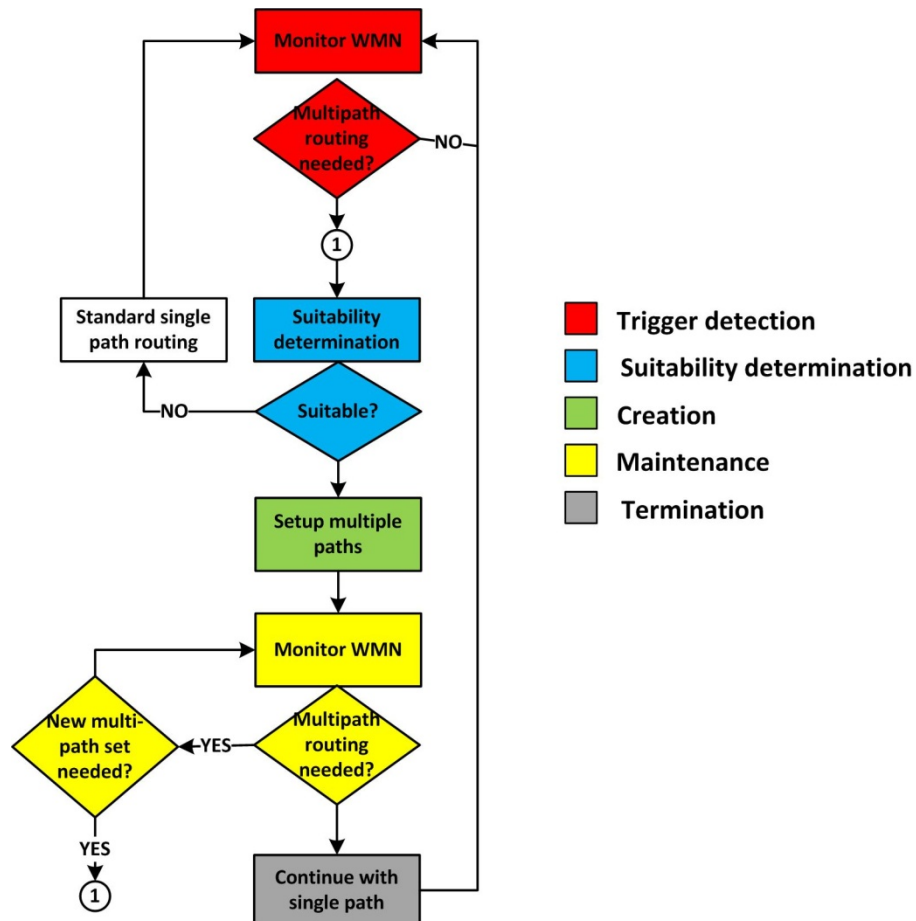


Figure 40: ON phases covered by the algorithm

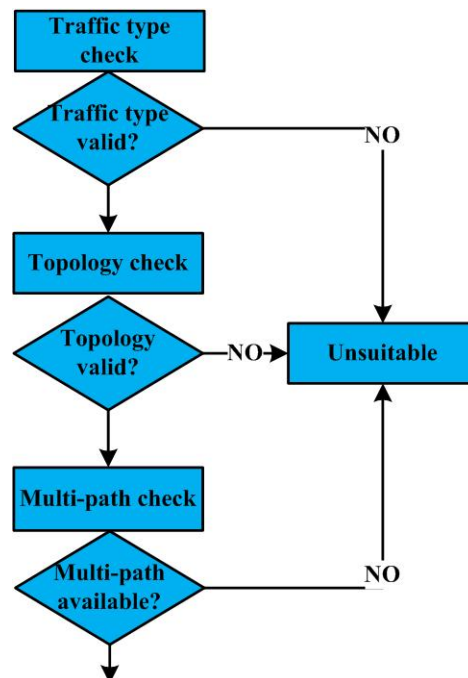


Figure 41: Suitability determination phase of the algorithm

When trigger is detected, or predicted, the ON suitability determination phase starts (see Figure 40). This phase is composed of three tasks performed in sequence. The task #1 is traffic examination with aim to determine whether or not the multipath routing is applicable on the current traffic

composition. Next, the task #2, which is topology check (see Figure 40) starts. The goal is to determine whether or not the given WMN topology allows for multiple paths to be formed in order to relieve the congestion at the node AP_i . Finally, task #3 of the suitability determination (see Figure 40) is performing a check on whether or not an appropriate path can be found, which will, in addition to the current path, provide aggregation of the available backhaul bandwidth on the access side of AP_i .

The suitability determination tasks execution sequence depicted in Figure 40 facilitates the fastest possible decision making. This is achieved by starting the suitability determination with task #1 which is the least demanding in terms of execution time. Determinations associated with task #2 are somewhat more demanding. Nevertheless the most demanding determination is left for the task #3 which is performed only if the previous two tasks return positive outcome and warrant further engagement of computational resources.

2.12.3 Integration in OneFIT architecture

The presented algorithm will be implemented as part of both, CSCI and CMON management systems.

Mapping of the algorithm on the CSCI:

- Context awareness: is achieved through SNMP monitoring of the underlying WMN. The same protocol is used for gathering contextual information regarding WMN nodes and performance of the wireless backhaul links.
- Operator policy derivation: initial set of algorithm triggers is defined, as well as set of rules for creation of ONs. These triggers and rules will evolve in time as algorithm encounters and solves new problems. Also, different types of traffic and their characteristics (applications and QoS requirements) are defined proactively. Defined policies are stored in the database of contextual data which is located in the core side of the network.
- Knowledge management: algorithm learns about efficiency of selected multiple path solutions through monitoring system. Obtained knowledge is used for improvement of the algorithm's efficiency. All of the gathered knowledge about underlying WMN, traffic patterns and efficiency of the algorithm is stored in the contextual database in the core side of the network.
- Decision making: phases of the decision making which are conducted by the algorithm are depicted in Figure 40. Multiple path check sub-phase of the suitability determination is performed within the CMON.

Mapping of the algorithm on the CMON:

- Context awareness: is ensured with system monitoring over SNMP protocol.
- Operator policy acquisition: defined rules and triggers are obtained from the centralized database of contextual information.
- ON creation: when appropriate paths set is found for providing requested bandwidth aggregation in the backhaul side of the WMN, the ON is created in order to support the objective.
- ON maintenance: system is monitored through SNMP protocol. Performance of the established ON is under constant evaluation.
- ON termination: if multipath routing ceases to perform in defined boundaries, or bandwidth aggregation is no longer needed, ON is terminated. Single-path OLSR continues to work normally.

MSC of the opportunistic backhaul bandwidth aggregation through multi-path routing is presented in Figure 42.

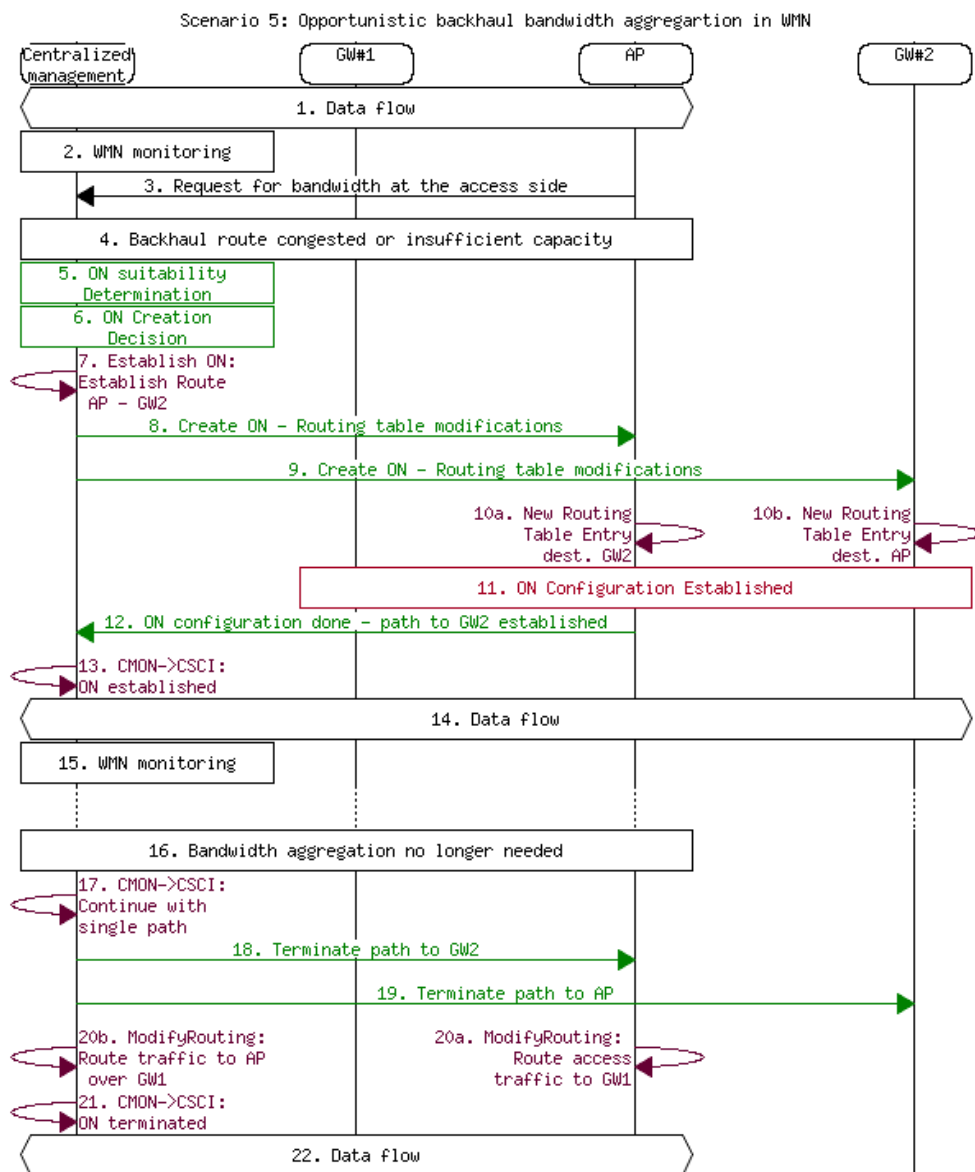


Figure 42: MSC of the backhaul bandwidth aggregation

As depicted in Figure 42, the majority of the ON related signalling is performed within the centralized management system where the presented algorithm for backhaul bandwidth aggregation resides. Only instructions for routing table modifications are sent towards the WMN nodes.

2.13 UE-to-UE Trusted Direct Path

2.13.1 Problem formulation and algorithm concept

The challenge addressed here is to establish a WLAN network between N devices (System 1) by using connections allowed by another technology (System 2). The N devices or users have double communication capabilities, since they can communicate using 2 different technologies (the one used by System 1 and the other used by System 2).

System 1 can be for instance an IEEE 802.11 WLAN (i.e., terminal devices are called stations (STA)) and System 2 can be a cellular network, for instance LTE (i.e., terminal devices are called User Equipments or UE).

At the beginning, we consider that System 1 is not yet communicating. The goal is to choose an Access Point (AP) for the set of the N devices, and an operating channel such that the per-link (node-to-node) QoS requirements are met. Therefore, the main challenges are in taking into account the following points:

- As System 1 is not yet deployed, the choice of the couple (AP, channel) should be based on prediction and not on measurements.
- Any node belonging to the set of the N nodes can be chosen to be the AP, and there is a set of M available channels that may be used. *A-priori*, any of the M channels may be used by other systems. Therefore, System 1 would have to share one of the M channels with other incumbent systems.
- System 1's AP and channel selection is based on the information received through System 2.

Moreover, the WLAN establishment (i.e. System 1) is under the following criteria:

- QoS requirements for all the WLAN members,
- power minimization requirements for all the WLAN members.

More specifically, the problem can be formulated as follows: given a set of M opportunistic channels and a set of N candidate stations, how to choose an AP and an operating channel that allow fulfilling the aforementioned criteria?

The underlying scenario is depicted in Figure 43: We face the problem of a WLAN creation (System 1) controlled by a WLAN Manager. The WLAN Manager is aware of the localization information of all the candidate stations via a cellular network for instance (System 2). The WLAN Manager could be an entity connected to the MME (3GPP entity) and it should have access to the localization information from a network entity called E-SMLC (Evolved-SMLC). In this case, the communication between the N candidate stations is performed over LTE since it is considered that the N candidate stations have double communication technology: cellular technology and WLAN technology. The WLAN Manager assigns the role of the AP to the selected station and triggers operation of the WLAN in the selected channel via the cellular network (System 2). After WLAN network is formed, the candidate stations will then start communicating through the AP and the channel proposed by the WLAN Manager. Therefore, the WLAN (System 1) is established with a help of another system or technology (System 2).

The stations essentially make measurements in the available channels and report them to the WLAN Manager. After running the AP and channel selection algorithm, the WLAN Manager informs the stations with the AP and channel choice for WLAN establishment.

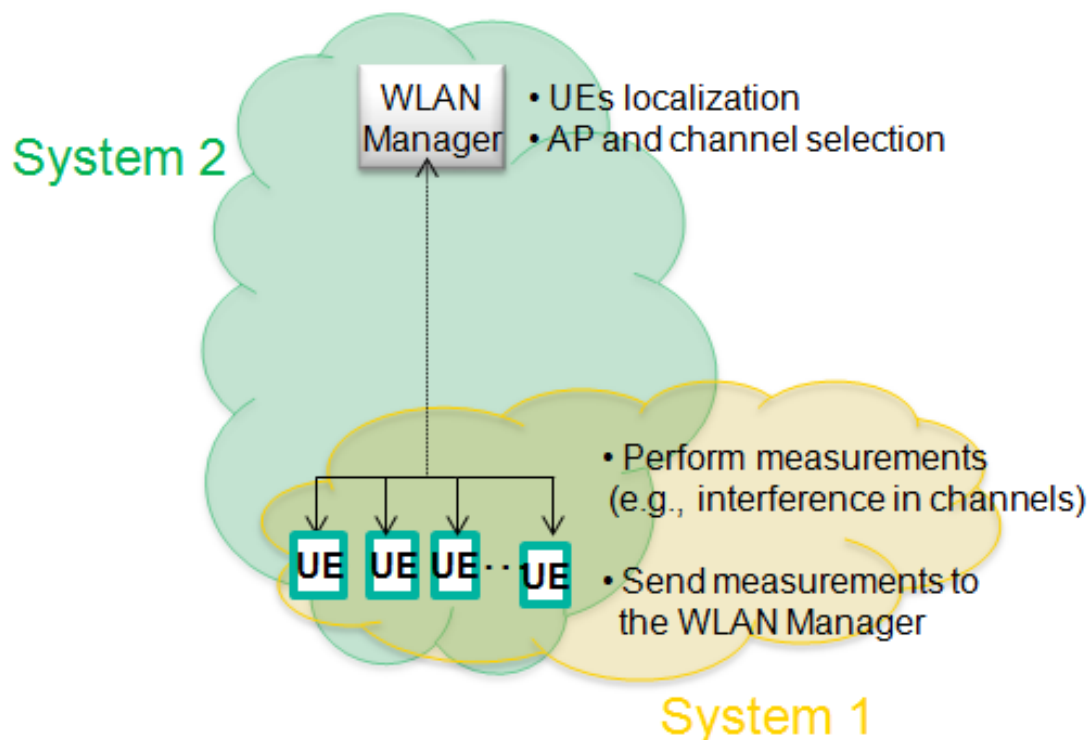


Figure 43: AP and Channel Selection during the creation of a WLAN

It is worth noting that the objective here is only the initial selection of an AP and an operating channel. When the network changes (connection of new stations, disconnection of existing stations or change in channel conditions), dynamic channel selection algorithms should be used to maintain the network service demand.

By providing means of establishing and maintaining an opportunistic WLAN through signalling over another existed network (e.g., cellular network), the current AP and channel selection algorithm addresses both the scenario 2 “Opportunistic capacity extension”, the scenario 3 “Infrastructure supported opportunistic ad-hoc networking”, the scenario 4 “Opportunistic traffic aggregation in the radio access network” and the scenario 5 “Opportunistic resource aggregation in the backhaul network”. Particularly but not only, the use cases “Coverage extension via an access point”, “Infrastructure offload”, “Resource utilization improvement and reduction of overhead for switching between common and dedicated channels” are addressed.

The algorithm can be mapped to the following ON lifecycles:

- **Creation:** the algorithm allows creating a WLAN as the WLAN Manager performs the algorithm to find the good choice of AP, channel and transmit power, and triggers the WLAN establishment via the cellular network.
- **Maintenance:** Once the WLAN is formed (i.e., the AP and the channel and the minimum required transmit power are found), changes are likely to occur: some stations can be going away from the coverage of the AP, and some others stations can be invited to join de WLAN because they have moved to the coverage of the AP. The proposed algorithm should therefore be performed in order to maintain the WLAN.

Although the proposed algorithm is not part of the Suitability determination, it is worth noting that this step is required to provide to the creation phase the request for WLAN establishment together with the WLAN requirements (such as the QoS and the power consumption requirements) .

2.13.2 Algorithm specification

The proposed algorithm relies on the various links QoS requirements to select, as the AP, the station that provides the highest among the worst links in the WLAN. More specifically, the algorithm estimates the QoS of all the links in all the available channels if potential station i (for $i=1, 2, \dots, N$) were the AP. In each AP-channel assumption, the algorithm finds the worst among all downlinks and uplinks. By comparing the worst links for all the AP-channel assumptions, the highest among the worst links is found; the corresponding AP and channel are chosen as the best choice of AP and channel.

In our studies, the QoS is a function of the simplified capacity. We define the simplified capacity of the link from station i to station j in channel ch as:

$$C(i, j, ch) = \log_2 \left(1 + \frac{P_i d_{i,j}^{-\alpha} G_{i,j}}{I_{j,ch} + n_{j,ch}} \right), \quad \text{for } i, j = 1, \dots, N \text{ and } ch = 1, \dots, M \quad (60)$$

Where:

- P_i is the transmit power of node i ,
- $d_{i,j}$ is the distance between the station i and the station j ,
- α is the path loss exponent which depends on different characteristics and especially on type of environment (e.g., Urban environment, where $\alpha \in [3, 4]$),
- $G_{i,j}$ is accounting for the antenna gain of both the transmitter i and the receiver j ,
- $I_{j,ch}$ is the interference measured in node j in channel ch ,
- $n_{j,ch}$ is the Gaussian noise in the receiver of station j in channel ch ,
- M is the number of channels,
- N is the number of stations,

It is worth noting that the simplified capacity does not take into account the fast fading. Therefore the simplified capacity can be seen as a static measure of the link quality. The greater is the simplified capacity, the greater the mean link QoS is. We define $C_0(j)$ as the target simplified downlink capacity to the station j . These target capacity is assumed to be the same in all the channels. Therefore, one can express the residual capacity in channel ch of the link station i to j as follows:

$$\Delta(i, j, ch) = C(i, j, ch) - C_0(j). \quad (61)$$

The residual capacity is a measure of link relative QoS. If the residual capacity is positive, then the required link QoS can be achieved, otherwise the link QoS cannot be achieved.

According to the previous definitions, if station i where the AP, the vector of links residual capacities, from station i to others (downlinks) and from other stations to station i (uplinks) is $\begin{pmatrix} \Delta(i, :, ch) \\ \Delta(:, i, ch) \end{pmatrix}$. Where the elements $\Delta(i, :, ch)$ and $\Delta(:, i, ch)$ are defined as:

$$\Delta(i, :, ch) = \begin{pmatrix} \Delta(i, 1, ch) \\ \Delta(i, 2, ch) \\ \vdots \\ \Delta(i, N, ch) \end{pmatrix}; \quad \Delta(:, i, ch) = \begin{pmatrix} \Delta(1, i, ch) \\ \Delta(2, i, ch) \\ \vdots \\ \Delta(N, i, ch) \end{pmatrix}. \quad (62)$$

Therefore, the residual capacity of the worst link can be expressed as follows:

$$\chi(i, ch) = \text{Min} \left(\begin{matrix} \Delta(i, :, ch) \\ \Delta(:, i, ch) \end{matrix} \right). \quad (63)$$

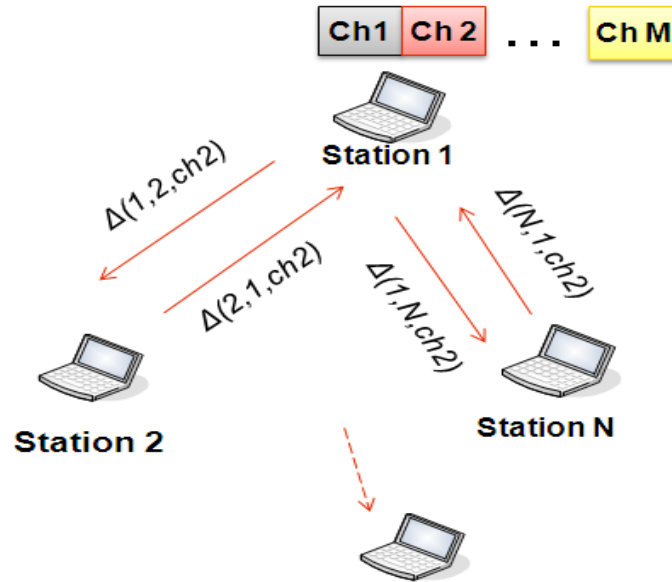


Figure 44: Worst link search under assumption that station 1 is the AP operating in channel ch2.

The best channel, if station i where the AP, is the channel that maximizes the vector $\chi(i, :)$:

$$[\Psi(i) \quad CH_{opt}(i)] = \text{Max } \chi(i, :), \quad (64)$$

where $\Psi(i)$ is the maximum of vector $\chi(i, :)$, and $CH_{opt}(i)$ is the index of the maximum in vector $\chi(i, :)$. Therefore, the index of the best channel, if station i where the AP, is $CH_{opt}(i)$. The vector Ψ is the vector with elements $\Psi(i)$ representing the best amongst the worst links if station i (for $i=1 \dots N$) were the AP.

$$\Psi = \begin{pmatrix} \Psi(1) \\ \Psi(2) \\ \vdots \\ \Psi(N) \end{pmatrix} \quad (65)$$

Therefore, the best AP corresponds to the maximum of vector Ψ :

$$[\text{BWRC} \quad \text{AP}_{\text{index}}] \leftarrow \text{Max } \Psi. \quad (66)$$

BWRC is the value of the maximum of Ψ or equivalently the **B**est among the **W**orst **R**esidual **C**apacities of all the links for all the channels. AP_{index} is the index of the best choice of AP among all the stations.

Finally, the index of the best channel is found as follows:

$$\text{Channel}_{\text{index}} \leftarrow CH_{opt}(\text{AP}_{\text{index}}) \quad (67)$$

The residual capacity BWRC can be sometimes negative. That is, for the best AP and channel choice, the QoS of the worst link cannot be reached for the current value of initial transmit power P_i . We then increase the transmit power P_i until BWRC is positive, therefore we guaranty that the QoS of both links can be reached for the final configuration AP, channel.

The AP and channel selection algorithm can be stated as follows:

Algorithm 10: AP and channel selection algorithm

```

1: for  $i=1$  to  $M$ 
2:    $P_i \leftarrow P_{\min}$  ;
3: end for
4: for  $ch=1$  to  $M$  do
5:   for  $i=1$  to  $N$  do
6:     for  $j=1$  to  $N$  do
7:
8:        $C(i, j, ch) \leftarrow \log_2 \left( 1 + \frac{P_i d_{i,j} G_{i,j}}{I_{j,ch} + n_{j,ch}} \right)$ ; /* Downlink capacity from node i to node J in channel ch
9:
10:       $\Delta(i, j, ch) \leftarrow C(i, j, ch) - C_0(j)$ ; /* Downlink residual capacity from node i to node J in channel ch
11:    end for
12:  end for
13:  for  $i=1$  to  $N$  do
14:     $\chi(i, ch) \leftarrow \text{Min} \left( \begin{matrix} \Delta(i, :, ch) \\ \Delta(:, i, ch) \end{matrix} \right)$ ;
15:  end for
16:   $[\Psi(i) \ CH_{opt}(i)] \leftarrow \text{Max} \chi(i, :)$ ; /*  $\Psi(i)$  is the value of the maximum of  $\chi(i, :)$  and  $CH_{opt}(i)$  is the index in vector  $\chi(i, :)$ 
17:  end for
18:   $[\text{BWRC} \ AP_{\text{index}}] \leftarrow \text{Max} \Psi$ ; /* where BWRC is the value of the maximum of  $\Psi$  and  $AP_{\text{index}}$  is
the index of BWRC in vector  $\Psi$ .
19:   $\text{Channel}_{\text{index}} \leftarrow CH_{opt}(AP_{\text{index}})$ ; .
20: while  $\text{BWRC} < 0$ 
21:    $P_i \leftarrow P_i + a$ ;
22:   Re-compute BWRC with the new value of  $P_i$ ;
23: end while
24: Return  $(AP_{\text{index}}, \text{Channel}_{\text{index}}, P_i)$ ;

```

The flow chart of the proposed algorithm is depicted on Figure 45.

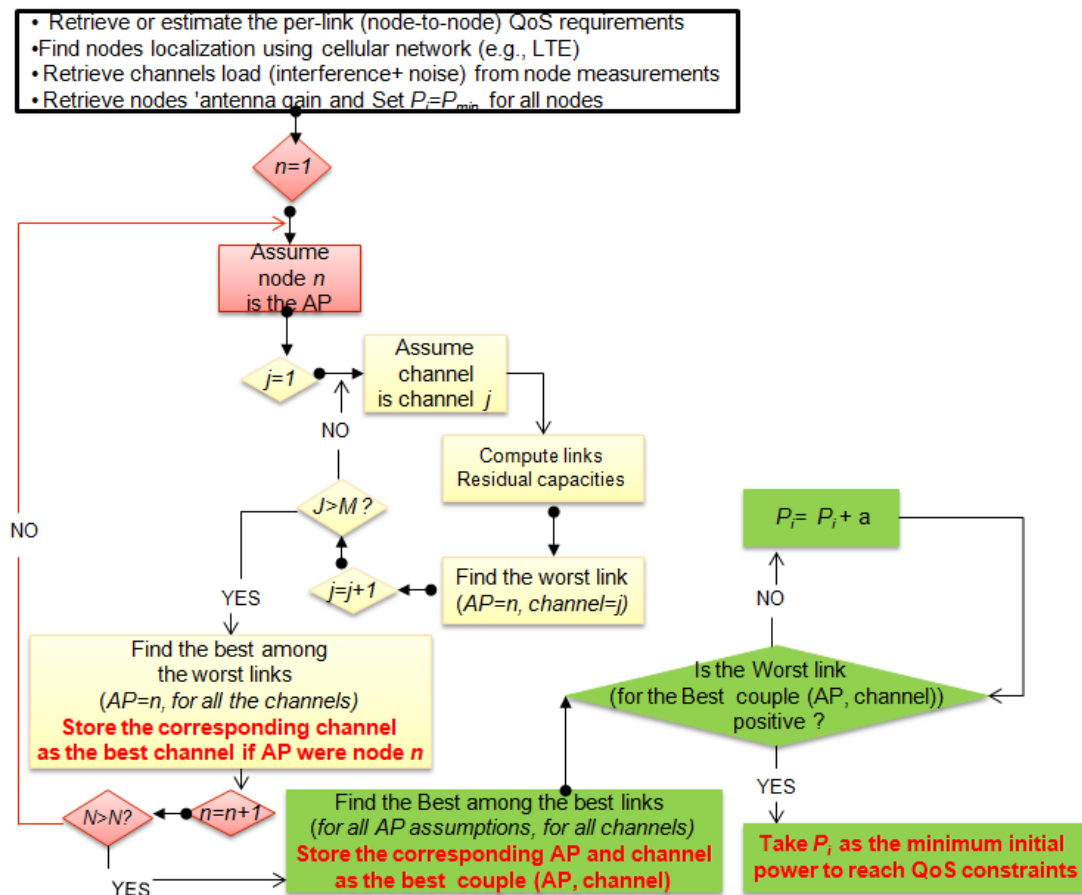


Figure 45: Flow chart of the proposed AP and Channel selection

2.13.3 Integration in OneFIT architecture

The proposed WLAN establishment algorithm can be mapped to both CMON and CSCI management systems in the infrastructure nodes (WLAN Manager and the candidate stations). The reasons of the WLAN creation (suitability determination), the service demands, and the WLAN requirements should be mapped to the CSCI management system. The WLAN creation and maintenance are mapped in the CMON system.

2.14 Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

2.14.1 Problem formulation and algorithm concept

The algorithm addresses the OneFIT scenario 5 “Opportunistic resource aggregation in the backhaul network”. More precisely, the use case related to aggregation of backhaul storage resources of WMNs is addressed. Algorithm’s task is to, based on contextual data gathered from the WMN environment and end users, provide appropriate WMN node selection for multimedia content placement and distribution. The criteria for node selection is based on request distribution, popularity of multimedia content, status of caching storage of WMN nodes and user’s behaviour (mobility, viewing patterns and used devices). First, algorithm will select WMN nodes for proactive content placement based on detected and predicted contextual parameters (request distribution, content popularity and user’s behaviour). As the context parameters change, the content will be redistributed in order to accommodate context changes. ONs are created among WMN nodes with stored content for the purpose of providing means (communication channels and new paths) for

peer-to-peer (p2p) content distribution among WMN APs and content delivery from WMN APs (with stored content) to requesting users, which are connected to WMN APs without stored content.

The algorithm can be mapped to ON lifecycle phases as follows:

- Suitability determination –algorithm will provide analysis of suitability for placement of particular content on WMN APs. If content is to be placed in the backhaul storage pool of the WMN, algorithm will provide set of nodes which are considered to be candidates for content placement.
- Creation – algorithm will select optimal subset of candidate nodes for proactive content placement/distribution.
- Maintenance – the algorithm will detect context changes (user mobility, content popularity, status of nodes and their storage space, user request re-distribution), which require content redistribution and reconfiguration of ONs created to support p2p content delivery among WMN APs.

2.14.2 Algorithm specification

Algorithm for node selection for proactive and reactive content distribution in WMNs

Algorithm for node selection for content placement on WMN APs is based on a mathematical model in form of mixed integer linear program (MILP). This model takes into account distribution of users' requests, available storage capacity of WMN nodes, and capacity of the links in WMN backhaul. Contextual data (database in Figure 46) regarding history of requests for content, user's mobility, content profiles, status of WMN backhaul links and status of storage area in WMN nodes will be used for derivation of knowledge regarding:

- Temporal and spatial distribution of requests for particular content.
- User's mobility patterns.
- Traffic patterns in WMN backhaul links.

This knowledge will be used for triggering content distribution to WMN nodes and among them and for decision making mechanism of the algorithm. Proactive caching provides initial network access node selection for placement of video files. To be able to achieve cognitive placement of files, proactive caching mechanism must take into account the following contextual data:

- Video content popularity (on local and more broad level);
- Spatial and time distribution of user requests;
- Profile of end users (their mobility patterns, viewing patterns, equipment capabilities, QoS requirements);
- Status of backhaul nodes (available storage in APs, popularity of currently cached data and available bandwidth for streaming...);
- Backhaul traffic patterns.

By processing above mentioned contextual data, proactive caching mechanism selects appropriate WMN APs and places certain number of copies of multimedia content (video file's chunks) into their storage space.

Reactive caching mechanism relies on monitoring system to detect changes in status of the WMN APs and users' requests which will trigger redistribution of content among WMN APs (trigger levels are defined by the service provider). Contextual data that is taken into account for this mechanism are:

- Changes in backhaul traffic (in order to avoid congestion on some backhaul links);

- Changes in spatial user request distribution (more requesting users move from one AP to another – changes not covered by the detected mobility patterns);
- Changes in status of WMN nodes (node down);
- Popularity of files ready for proactive caching (if very popular file has to be cached in access points then storage space for it has to be provided).

Collected contextual data is stored in centralized database and used for derivation of cognition about network environment and system performance. By using this cognitive information, algorithm is able to derive appropriate response to previously encountered situations and to predict best response for newly encountered problems.

When the algorithm detects a user's request for file f , which contains N chunks (k) and if that particular file is not locally cached in WMN access points, then the algorithm has to decide whether or not to cache this file or to proceed with streaming from source server (see Figure 46). If decision is made to cache new file in WMN APs, then candidate nodes have to be detected and selected. During the streaming process to the end user, chunks of video file f are cached on selected APs and, at the same time, contextual data about system performance and resource utilisation is collected.

If requested video file is stored on WMN access points, algorithm needs to determine candidate nodes for streaming chunks of video file to the requesting user. Previously collected contextual data and derived knowledge is used for selection of candidate nodes and derivation of streaming schedule that provides the best system performance and network resource utilisation. During the streaming process algorithm gathers contextual data from database (filled by monitoring system) and if changes in system environment reach some threshold (event triggered change) re-caching possibilities are examined. If re-caching is not possible or is not expected to solve current problem, then streaming is continued from source server. During streaming session from the source server, system is monitored and streaming is continued from APs when system environment status allows it. If re-caching is selected as the solution for the encountered problem, then appropriate APs are selected and some chunks of the video file are moved among APs. When content redistribution process finishes, the new streaming schedule is derived and streaming session continues. Contextual data about system performance, resource utilisation and end user perceived QoS are gathered during algorithm cycle and saved in contextual database for further knowledge derivation.

For every user request ON will be created among selected WMN APs to support algorithm execution which will provide aggregation of storage resources in order to locally stream as much chunks of requested video file as possible. ON will provide support for reactive caching mechanism by enabling gathering and exchange of contextual data which will enable detection of any changes in access network environment. When values of gathered contextual data change above certain threshold, reactive caching mechanism will start the re-caching process over the created ON.

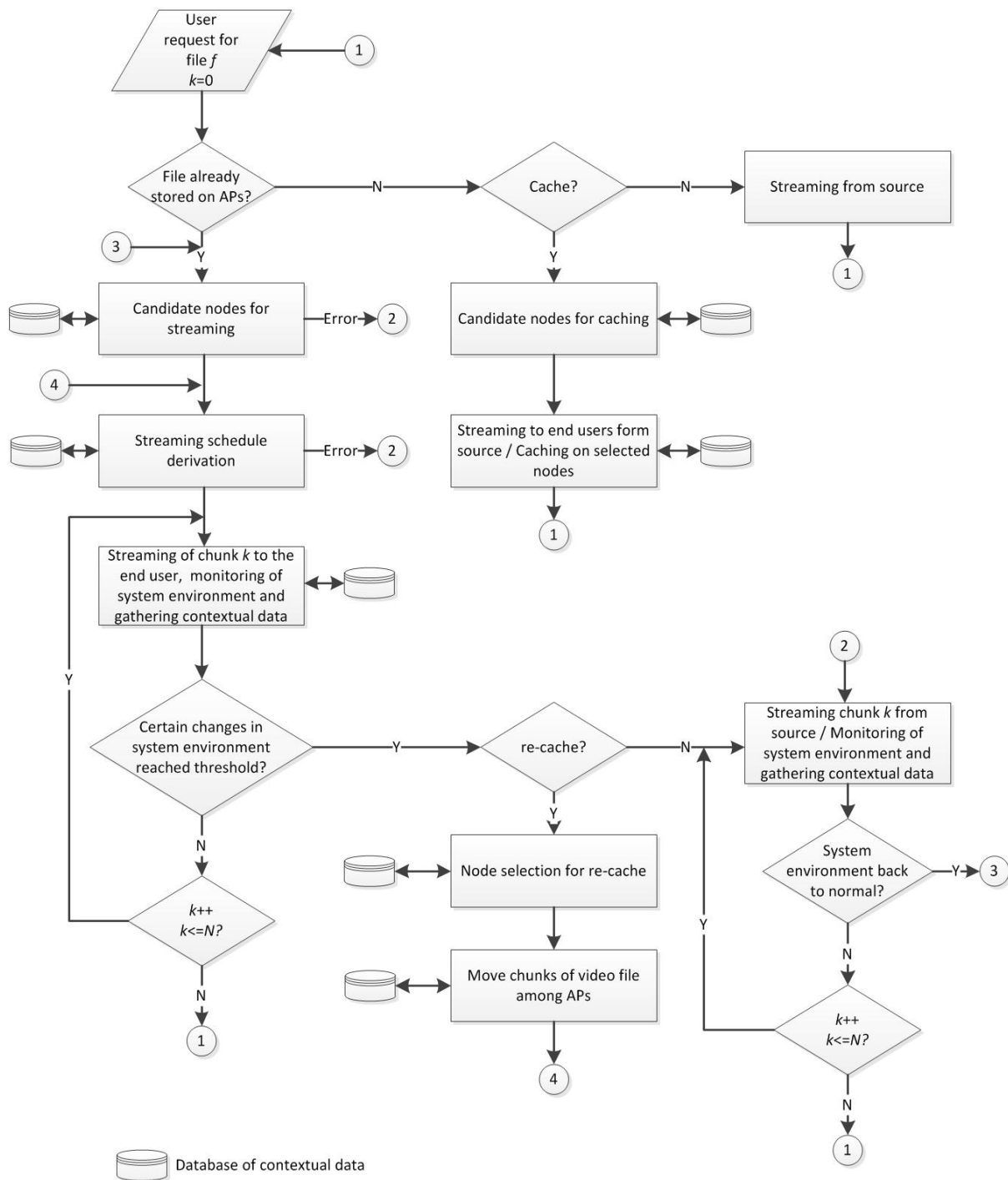


Figure 46: Algorithm for context aware content distribution to and among WMN APs

The MILP model of a pervasive wireless mesh CDN system is derived from multi-commodity flow problem with multiple sources of video files (access points and source servers) and multiple sinks (requesting users). In order to tackle with problem at hand we have introduced super source nodes in network flow graphs for every video file in the system (video file \leftrightarrow commodity). Therefore, for every file, which is to be placed in the caching storage of the access points, we introduce a superficial (super source) node named All Replica Containing File n (ARCF n) and connect it to all other network nodes considered to be legitimate targets for placement of replica of file n .

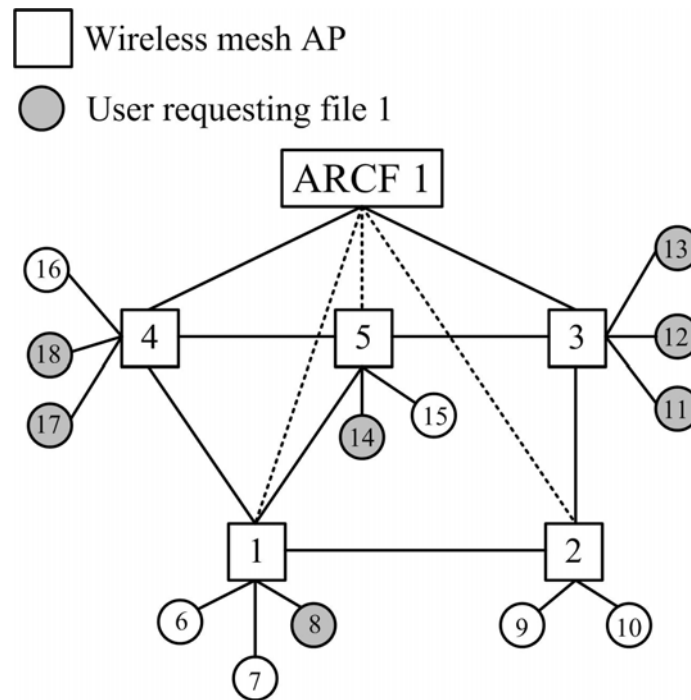


Figure 47: Graph of the simple WMN with ARCFn node added

All WMN access points are considered as candidates for replica placement. Regarding these facts, ARCFn node for every file will be connected to every WMN access point in the network graph. Connecting edges are directed from ARCFn node to all candidate nodes and have weight equal to zero in order not to change the ADTL value. When needed number of copies of video file and user request distribution are derived, ARCFn node will be used as super source node, which will transform the multi-source/multi-sink multi-commodity flow problem of the original network flow graph to the single-source/multi-sink multi-commodity flow problem. In Figure 47 is depicted ARCFn node concept for simple pervasive WMN network. All access points are considered to be candidates for replica placement. Therefore, there are edges from ARCF1 to all nodes representing access points. If two copies of video file 1 are to be placed in caches of WMN access points, then solid lines, representing edges from ARCF1 to access points 4 and 3, mean that these access points are selected as optimal solutions for replica placement problem.

The MILP model for selection of optimal subset of candidate WMN nodes, on which to proactively place a copy of multimedia content, is defined as follows:

Table 1: MILP model variables and parameters

E	Set of edges of a starting wireless mesh network
V	Set of nodes of a starting wireless mesh network
V_i^{IN}	In-neighbourhood set of nodes for node i
V_i^{OUT}	Out-neighbourhood set of nodes for node i
V_{GW}	Subset of V containing WMN GW nodes
V_{AP}	Subset of V containing WMN APs
$ARCFn$	Virtual nodes added for delivery tree calculation convenience. ARCFn stand for "All Replica Containing File n "
K	Set of edges that are incident to ARCF nodes

F	Set of files in the network
N^f	Number of copies of file f that are to be placed in network. This parameter is derived by taking into account predicted local popularity of a file and user request distribution
M^f	Total load for file f which directly equals to number of requesting users and consequently the popularity of file f
ω_{ij}	Cost of network edge (may represent different metrics or status of wireless links)
L_k^f	Requested load of node k for file f
X_{ij}^f	Load for file f over edge (i,j)
Y_{ij}^f	Integer (binary) variable, encoding the existence of edge from ARCF node i for file f to replica server j (indicating file placement on a WMN node)
Q_{ij}	Number of copies of files stored in network node j ("i,j" indexing since this node constraint is presented as a link constraint for the sake of model implementation)
q_{ij}	Storage capacity of network node j
M_{ij}^{LINK}	Maximum possible load over edge (i, j) (link capacity)
M_a^{AP}	Maximum load of AP a
M_g^{GW}	Maximum load of GW g

Objective function:

Minimize:
$$\sum_f \sum_{(i,j)} \omega_{ij} X_{ij}^f \quad \forall ((i,j) \in (E \cup K), f \in F) \quad (68)$$

Subject to:

$$\sum_{i,(i,k)} X_{ik}^f - \sum_{j,(k,j)} X_{kj}^f = L_k^f \quad \forall ((i,j) \in (E \cup K), f \in F) \quad (69)$$

$$X_{ij}^f \leq M^f Y_{ij}^f \quad \forall ((i,j) \in K, f \in F) \quad (70)$$

$$\sum_{(i,j)} Y_{ij}^f \leq N^f \quad \forall ((i,j) \in K, f \in F) \quad (71)$$

$$Q_{ij} \leq q_{ij} Y_{ij}^f \quad \forall ((i,j) \in K, f \in F) \quad (72)$$

$$Q_{ij} \geq \frac{X_{ij}^f}{M^f} \quad \forall ((i,j) \in K, f \in F) \quad (73)$$

$$\sum_{f \in F} (X_{ij}^f + X_{ji}^f) \leq M_{ij}^{LINK} \quad \forall (i,j) \in E \quad (74)$$

$$\sum_{f \in F} \sum_{k \in V_a^{OUT}} X_{ak}^f \leq M_a^{AP} \quad \forall a \in V_{AP} \quad (75)$$

$$\sum_{f \in F} \sum_{k \in V_g^{OUT}} X_{gk}^f \leq M_g^{GW} \quad \forall g \in V_{GW} \quad (76)$$

$$X_{ij}^f \geq 0 \quad Q_{ij} \geq 0 \quad Y_{ij}^f \in \{0,1\} \quad \forall ((i,j) \in (E \cup K), f \in F) \quad (77)$$

Constraint (69) is the flow conservation for every network node. The maximum number of nodes selected for replica placement is less or equal to the derived number of copies of file f (71). Constraint (72) represents limited storage space on APs. Constraints (70) and (73) give the connection between model variables (i.e. if Q_{ij}^f for one node is 0, then nothing can be streamed from that node, and corresponding X_{ij}^f for the edge from ARCFn to that candidate node is also 0). Constraint (74) imply that maximum flow over link (i, j) is limited to M_{ij}^{LINK} . Each link consists of two directed edges, modelling two-way communication. Constraints (75) and (76) depict that maximum flow out of AP and GW nodes is constrained to M_a^{AP} , M_g^{GW} respectively.

Mobile nodes (MNs) model motion of users. User connects to the nearest AP and request files. Each user can request only one file in a given time moment. Bit-rate for a requested file is guaranteed during the time needed for file download.

2.14.3 Integration in OneFIT architecture

The algorithm can be mapped to both CMON and CSCI management systems in the infrastructure nodes (WMN APs and centralized management server) as shown in Figure 48. Context awareness is provided by the algorithm by inspecting contextual information from contextual database which is filled by the monitoring system. Changes in relevant contextual parameters trigger the suitability determination phase (for creation of new ON or reconfiguration of the existing one). Suitability determination in CSCI will provide answers regarding whether or not to store particular content on WMN APs, how many copies and to select candidate nodes for content placement. Creation phase in CMON will select optimal subset of candidate nodes for placing copy of the content. For content delivery service, information regarding profile of end users, content and their connections is of crucial importance for providing context aware, adaptive content distribution and delivery.

The proposed algorithm has a main part which is the presented MILP model for optimal WMN node selection. The contextual information necessary for this model are:

- User request distribution (time and spatial)
- User's mobility
- Backhaul traffic in WMN and status of backhaul links (available capacity)
- File popularity
- Status of the storage space in WMN nodes

Some of these parameters are obtained from the service provider (user request distribution and file popularity) while other are gathered with the WMN monitoring system (user mobility, backhaul traffic and status of the WMN nodes and their storage). For the monitoring system a SNMP protocol is used, which is considered as one variant of the C4MS protocol for contextual data gathering (see M5.2). C4MS requests can be sent from the management system of the CDN to the WMN monitoring system for gathering necessary contextual data which is used for node selection process.

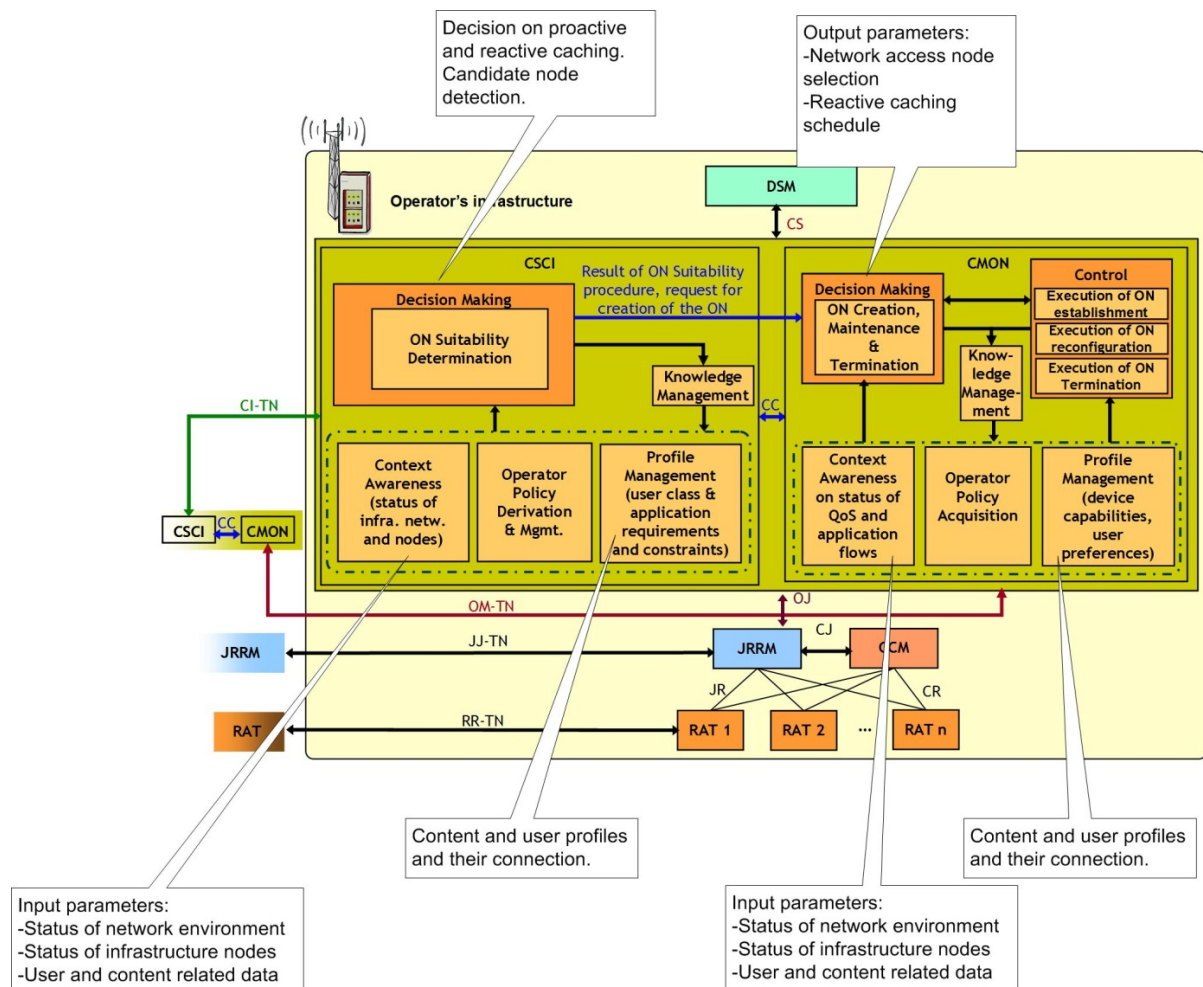


Figure 48: Algorithm placement in OneFIT functional architecture

2.15 Capacity Extension through Femto-cells

2.15.1 Problem formulation and algorithm concept

The problem considered in this section is the capacity extension of congested infrastructure through the exploitation of nearby femtocells. More specifically, an area is considered which contains a macro BS, terminals served by the BS and femtocells within the area of the BS. At some point, the macro BS faces congestion issues due to the traffic by the macro-terminals. The solution provided in this section is to offload the traffic of a proportion of the macro-terminals to the femtocells, through the creation of an ON among the terminals and the femtocells. The main objective of the algorithm, namely Dynamic Resource Allocation (DRA) that will provide the solution is not only to reroute macro-terminals to the femtocells, but also allocate the minimum possible power level to femtocells, that is required to cover the most users possible. In addition, the algorithm exploits the RDQ-A algorithm [8] in order to assign terminals to femtocells and QoS to terminals. Furthermore, the algorithm utilizes an objective function (OF) to evaluate the quality of each solution. Figure 49 illustrates the concept of the DRA algorithm.

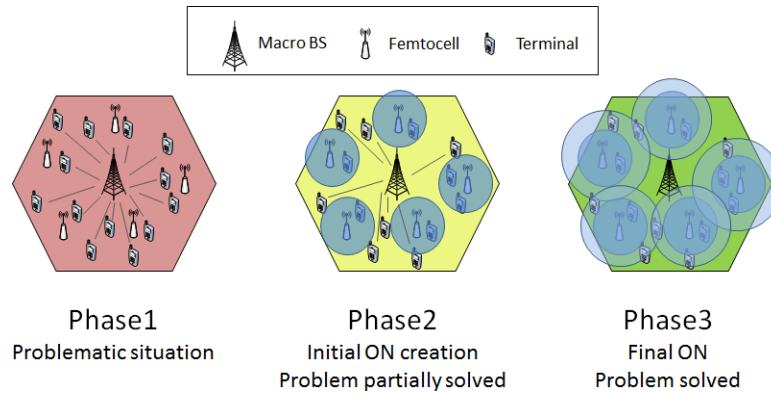


Figure 49: The concept of the DRA algorithm

The DRA algorithm uses as input the capabilities of the BS (e.g. RAT, capacity, etc.) that faces congestion issues. In addition it utilizes the capabilities of the set of the available femtocells (e.g. capacity, possible transmission power levels, etc.) and the capabilities of the macro-terminals and their traffic requirements.

The technical challenge of the DRA mechanism is relevant to the Scenario 2: “Opportunistic capacity extension” which was identified in [2], and specifically for Use case 2: “Macro-cell/femto-cell management”, where resources are allocated to femtocells which are integrated then to ONs.

Within the ON lifecycle, the DRA problem considered here is applicable in the ON creation phase. More specifically, as soon as a macro BS faces congestion issues the DSONPM is notified and the solution mechanism is triggered. If femtocells exist within the area of the congested BS, the DRA algorithm is executed in the CMON of the BS in order to offload terminals to the femtocells.

2.15.2 Algorithm specification

2.15.2.1 Mathematical formulation

Let F be the set of femtocells and let B be the set of macro BSs, while the set of terminals (users) will be denoted with U . Moreover, it is presumed that femtocells can be configured to discrete power-levels, i.e. a percentage of their maximum transmission power. Therefore, PL will denote the set of possible power levels. In addition, the following decision variables are considered:

$$X_{ij} = \begin{cases} 1, & \text{if user } i \in U \text{ is assigned to } j \in F \cup B \\ 0, & \text{otherwise} \end{cases} \quad (78)$$

$$Y_{kj} = \begin{cases} 1, & \text{if power-level } k \text{ is assigned to femto } j \in F \\ 0, & \text{otherwise} \end{cases} \quad (79)$$

$$N_{ijk} = \begin{cases} 1, & \text{if user } i \in U \text{ can be covered by femto } j \in F, \text{ configured at power-level } k \\ 0, & \text{otherwise} \end{cases} \quad (80)$$

In order to calculate the coverage of a femtocell according to its transmission power, the propagation model proposed by the authors in [9] is used.

The allocation problem is an optimization problem where an OF will be minimized, satisfying a number of constraints. Accordingly, the overall optimization problem can be formulated as follows:

$$\text{Minimize } OF = \sum_{j \in F} \sum_{k \in PL} CP_{kj} + \sum_{j \in F} \sum_{\substack{j' \neq j \\ j' \in F}} (\phi_j - \phi_{j'})^2 + \sum_{i \in U} \sum_{j \in F \cup B} X_{ij} \cdot d_{ij} + \sum_{j \in F \cup B} \phi_j \quad (81)$$

subject to:

$$\sum_{j \in F \cup B} X_{ij} = 1, \forall i \in U \quad (82)$$

$$\sum_{k \in PL} Y_{kj} = 1, \forall j \in F \quad (83)$$

$$N_{ijk} \leq Y_{kj}, \forall i \in U, j \in F, k \in PL \quad (84)$$

$$X_{ij} \leq N_{ijk} \cdot Y_{kj}, \forall i \in U, j \in F, k \in PL \quad (85)$$

$$\phi_j \leq cap_j, \forall j \in F \cup B \quad (86)$$

where

$$\phi_j = \sum_{i \in U} (X_{ij} \cdot b_i), \forall j \in F \cup B \quad (87)$$

$$CP_{kj} = \sum_{k \in PL} (Y_{kj} \cdot l_k \cdot P_j) \quad (88)$$

The load of a BS/femtocell j in terms of bits per second (bps) is denoted with ϕ_j , b_i is the bandwidth of terminal i in bps, cap_j is the capacity of BS/femtocell j in terms of bps and d_{ij} is the Euclidean distance of terminal i from BS/femtocell j in metres. P_j denotes the maximum transmission power of femtocell j in Watts, while CP_{kj} is the current transmission power of femtocell j configured at power-level k . l_k depicts the proportion of the maximum transmission power to which a femtocell is configured to operate (e.g. $l_1=0.5$). Finally, the coverage of a femtocell j is denoted with cov_j and is a function of the current transmitted power CP_{kj} .

The OF in (81) tracks the power consumption of the femtocells, the load balancing factor among femtocells, the distance among terminals and BSs/femtocells and the bandwidth consumption of the femtocells from the users that are served through them. More specifically, the first term of the function is the power consumption of the femtocells. The second term is used as a load balancing factor and is the load difference between each femtocell. The third term expresses the distance among terminals and BSs/femtocells. Lastly, the fourth term depicts the bandwidth consumption of the femtocells by the terminals. As far as the constraints are regarded, relation (82) depicts that each terminal is served by one and only one BS or femtocell. Relation (83) denotes that every femtocell can be configured to operate at only one power-level. Relation (84) expresses the fact that a terminal cannot be covered by a femtocell which operates at power-level k , if the power-level is not assigned to the femtocell. Relation (85) depicts that a terminal cannot be served by a femtocell operating at power-level k , if the terminal is not covered by the femtocell or if the power-level has not been assigned to the femtocell. Finally, relation (86) illustrates the fact that the capacity of a BS or femtocell must be at least equal with the sum of the load of all the terminals that are connected to it. Therefore, high power level assignment to femtocells has a negative impact to the OF value. In addition, the unbalanced distribution of traffic to the femtocells also has a negative impact. Moreover, while more terminals are assigned to femtocells, the distance from their serving infrastructure decreases which leads to improved solutions.

2.15.2.2 Algorithm inputs and outputs

The input parameters used by the aforementioned algorithm are listed below:

- A macro BS and its capabilities (e.g. RAT, capacity, etc.)
- A set of femtocells and their capabilities (e.g. capacity, possible transmission power levels, etc.)
- A set of terminals within the coverage of the macro BS and their traffic requirements

The output that is provided by the algorithm is the following:

- Power allocation to femtocells
- Distribution of terminals to femtocells
- Assignment of QoS to terminals

2.15.2.3 Algorithm operation and functional entities

In order to perform the resource allocation to femtocells, the DRA algorithm operation is based on the following functional entities:

- The Context Awareness (CA) entity of the CSCI, which is responsible for monitoring the status of the infrastructure network. In addition, it involves information about node capabilities (e.g. their status, location, mobility level, etc.).
- The Decision Making (DM) entity of the CSCI, which identifies the terminals that are suitable to be redirected to the femtocells, e.g. terminals with low mobility level. For that purpose the DM entity interacts with the CA entity.
- The Profile Management (PM) entity of the CMON, which includes terminals capabilities (e.g. possible operating RATs) and user preferences which are required for the decision making.
- The Operator Policy Acquisition (OPA) entity of the CMON which obtains and manages the policies which are being defined by the operator.
- The Decision Making entity of the CMON, which is responsible for assigning the appropriate resources to the femtocells and QoS to terminals. Therefore, the DRA algorithm is executed in this functional entity. The DM entity of the CMON interacts with the PM and OPA entities in order to acquire information required to compute the solution.

2.15.2.4 Dynamic Resource Allocation to femtocells

The functionality of the algorithm can be described in steps as follows. At *Step 1* the algorithm starts by configuring all femtocells to operate at their minimum power-level. At *Step 2*, for this minimum power allocation, which corresponds to a minimum coverage, the terminals are assigned to femtocells using a variation of the RDQ-A algorithm [8]. *Step 3* inspects whether all terminals are assigned to femtocells or if all femtocells have reached their maximum transmission power the algorithm ends. If not, the launch of m sub-problems is triggered at *Step 4*, where m is the number of femtocells that have not reached the maximum transmission power. At each sub-problem, the power-level of a different femtocell is increased to the next power-level resulting to different power-allocations $(A_{PF})_1, \dots, (A_{PF})_m$. Each sub-problem is processed simultaneously at *Step 5*. More specifically, for each sub-problem the RDQ-A algorithm is executed and the assignment A_{UF} of terminals to femtocells and the assignment A_{QU} of QoS to terminals are computed. The selection of the best triplet takes place at *Step 6*, in terms of minimization of the $OFofrelation$ (81). Finally, the algorithm performs a transition to *Step 3*.

After the termination of the above steps, the femtocells are configured to the power level at which they lastly acquired at least one terminal. The reason is that otherwise all femtocells could be configured to operate to their maximum transmission power.

Algorithm 11 : Dynamic Resource Allocation to femtocells

```

FOR each  $f$  in  $F$ 
  SET currentTransmissionPower( $f$ ) to minTransmissionPower( $f$ )
  STORE currentTransmissionPower( $f$ ) in PowerAllocation[ $f$ ]
END FOR
SET TerminalAssignment to RDQA.GetResult(PowerAllocation)

```

DO

SET F_n to $\{f \text{ in } F : \text{currentTransmissionPower}(f) < \text{maxTransmissionPower}(f)\}$

SET m to $|F_n|$

FOR $i=0$ to m

SET SubProblem[i].Femtos to F_n

END FOR

FOR each SubProblem[i]

Choose one different f_i from SubProblem[i].Femtos

SET currentTransmissionPower(f_i) to nextTransmissionPower(f_i)

STORE currentTransmissionPower(f_i) in SubProblem[i].PowerAllocation[f_i]

SET Subproblem[i].TerminalAssignment to RDQA.GetResult(SubProblem[i].PowerAllocation)

END FOR

SET BestSolution.AcquiredTraffic to -1

FOR each SubProblem[i]

IF SubProblem[i].AcquiredTraffic > BestSolution.AcquiredTraffic **THEN**

SET BestSolution to SubProblem[i]

END IF

END FOR

WHILE **NOT** (allTerminalsAssignedToFemtos(TerminalAssignment))

OR AllFemtocellsReachedMaxPower(PowerAllocation))

2.15.3 Integration in OneFIT architecture

The functional entities aforementioned to section 2.15.2.3 have a direct mapping to the entities of the OneFIT architecture as illustrated at Figure 50.

The aforementioned DRA algorithm is associated with the ON creation functionality. The DRA intends to assign resources to femtocells, as well as QoS to terminals. The procedure can be supported by means of the C4MS messages that have been defined in D3.3 [7]. In particular, Figure 51 presents the associated message sequence chart for the capacity extension through femtocells scenario.

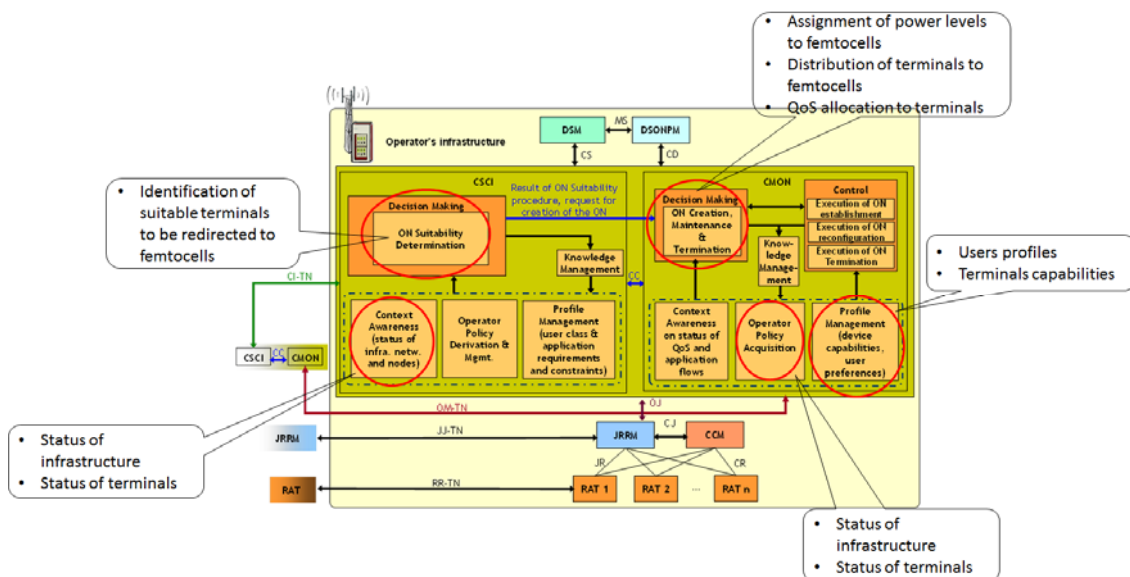


Figure 50 : Mapping of the DRA concept functional entities to the OneFIT functional architecture

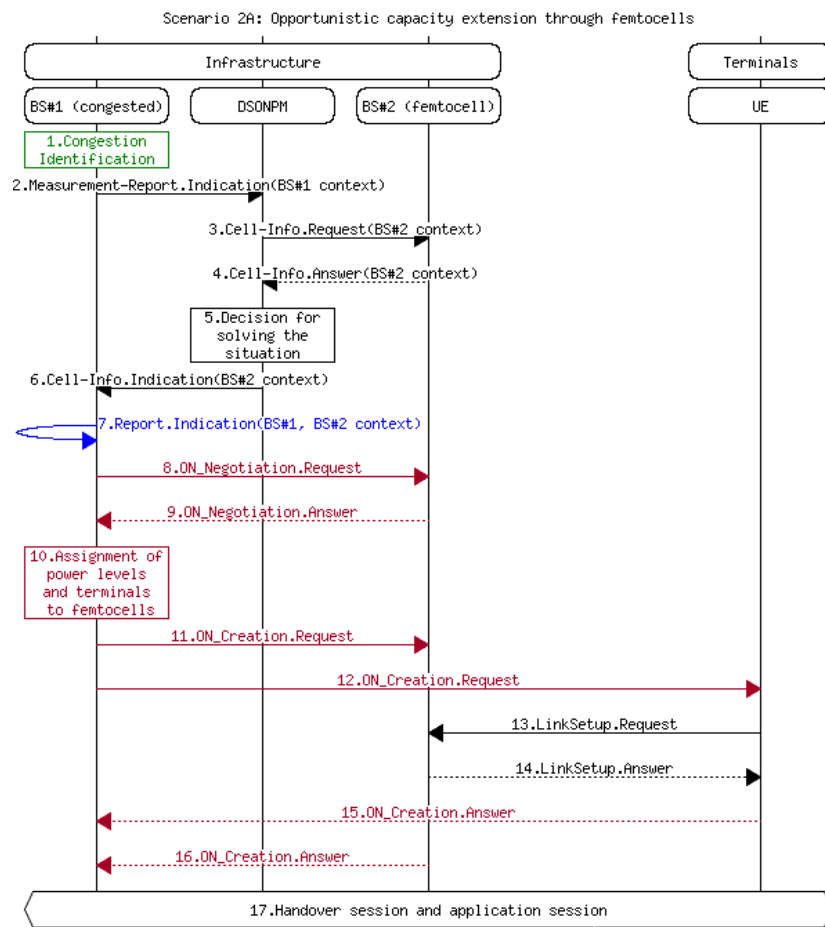


Figure 51: Message Sequence Chart for the capacity extension through femtocells scenario

2.16 Support activity to validate ON algorithms on an offloading-oriented real-deployment testbed

2.16.1 Problem formulation and algorithm concept

2.16.1.1 Rationale

The activity described next is focused on the assessment of the joint performance of some of the previously described algorithms in a controlled scenario and under a set of restrictions. The final objective behind these tests is to take advantage of the results to elaborate some recommendations for the implementation of an ON-based macro-to-femto offloading mechanism.

Therefore, we will evaluate the feasibility of using an Opportunistic Network approach to develop a macro-to-femto offloading procedure in LTE. Focus will be set on some of the algorithms of the life-cycle of ONs that enable such offloading mechanisms. In summary, algorithms that allow diverting traffic from the macro layer into an opportunistic set of femtonodes for coverage, capacity or quality enhancement purposes.

2.16.1.2 Test scenario

This activity will include a number of simulations that will be conducted over a pre-defined test scenario. It comprises a LTE networking in the 2600MHz band, using both 10 and 20 MHz bandwidths. It is located in an urban (Manhattan-like) area selected from real cartography of Barcelona city centre. It covers about 2 km², and 11 macro stations (eNBs) are located in their actual

positions. An additional layer of 291 femtos (eHNBS) has been set based on business estimations of real future deployments.

To avoid artefacts in the results of the edges of the scenario, a smaller focus area has been defined, with only 5 macros and 126 femtos. Main results will be referred to this focus area.

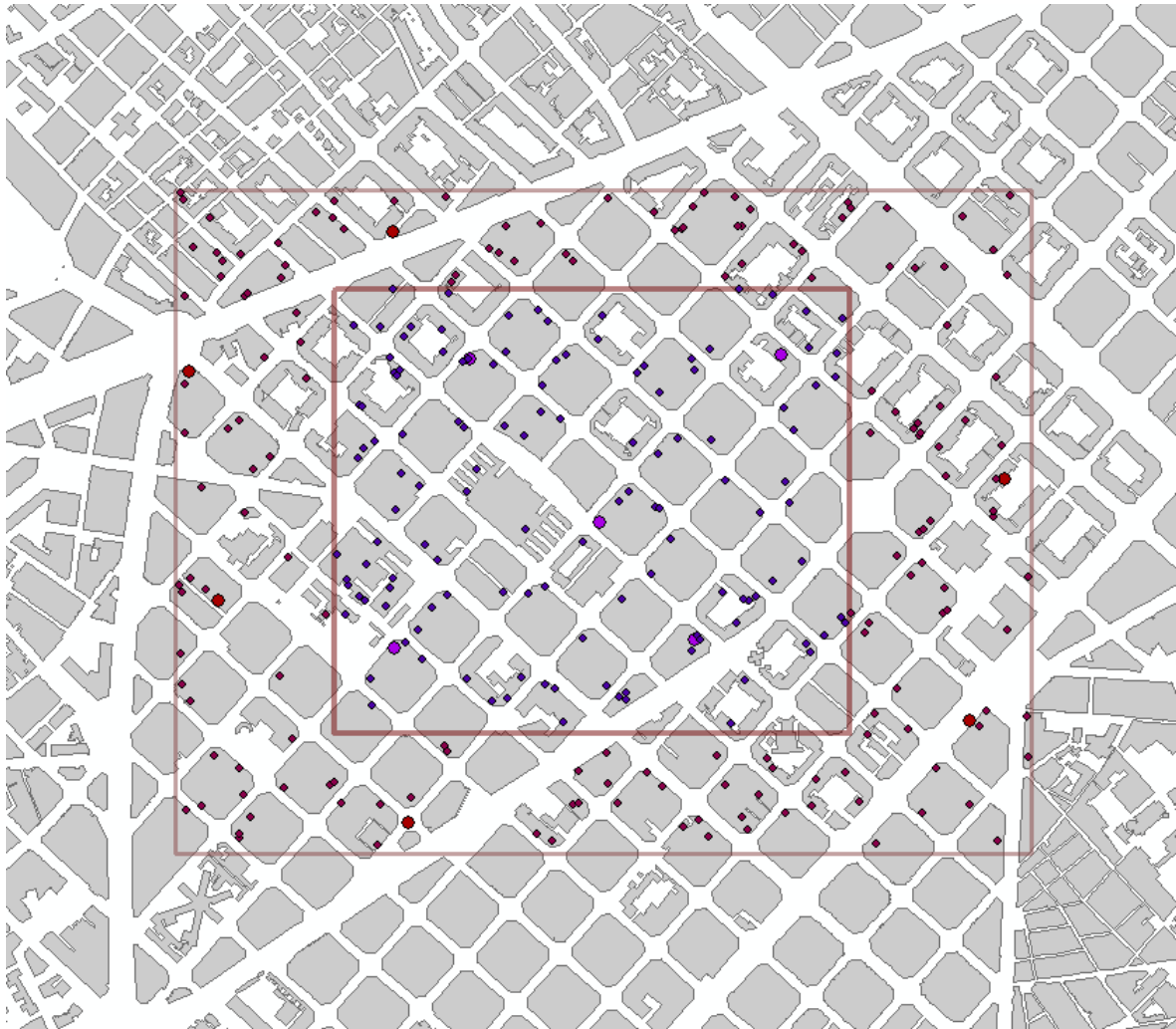


Figure 52: Base LTE test scenario and focus area

This base scenario can be easily adapted to map some of the OneFIT target scenarios, namely:

- *OneFIT Scenario 1 (Opportunistic Coverage Extension)*: Some of the macro sectors of the base scenario will be turned off to create coverage gaps. Users immersed in these gaps will be able to connect to surrounding femtos by means of opportunistic networking.
- *OneFIT Scenario 2 (Opportunistic Capacity Extension)*: The number of simulated users will be increased in order to force the apparition of hotspots. Congested cells will be alleviated by transferring rejected and underachieving users to surrounding femtos on an opportunistic basis.
- *OneFIT Scenario 3 (Ad-hoc opportunistic network)*: A target throughput threshold will be set at different values in order to evaluate the suitability of the ON to support different bitrate-hungry ad-hoc applications. Underachieving users will then be opportunistically offloaded to the femto layer in order to reach the threshold.

The simulations will mainly be focused on the first stages of the ON lifecycle, addressing technical challenges related to the suitability determination and creation phases. In particular, the detection

of potential nodes and resources opportunities and the assessment of potential gains are some of the main topics that will be investigated.

2.16.2 Activity specification

The simulation procedure comprises the following stages:

- *Scenario fitting*: Configuration parameters from base scenario are adjusted to fit the objectives of the expected simulation.
- *Generation of users*: A number of UEs is generated and located in random or controlled positions. The exact number and features of users depends on the objectives of the simulation.
- *LTE simulation*: The LTE simulation kernel is executed in order to obtain the radio KPIs for each user in the scenario.
- *ON management*: The ON engine is started in order to simulate the creation of an Opportunistic Network according to the scenario's criteria. Some sub-stages follow:
 - *Candidate node identification*: The femtos and UEs that could be part of the ON are identified. The initial candidates for the ON are those UEs that have a femto as best server (or reasonably good interferer) but cannot connect to it due to not being part of its CSG. Underachieving users can be also considered as candidates in capacity- and QoS-related scenarios.
 - *Optimisation problem definition*: An objective function to select the nodes that definitively will form the ON has to be set (see, for example, the ones in sections 2.7 or 2.15). The exact definition of the objective function depends on the scenario to be simulated (e.g. the focus is to keep the load balance, to conserve energy levels of the UEs, to minimize the femto transmission power, etc.)
 - *Optimisation solving*: The aim is to find the combination of UEs that should be transferred from the macro to the femto layer, which optimizes the objective function. Even if the number of candidate users is too high, the previous knowledge of the function and the scenario allows pre-calculating an initial allocation of users (e.g. allocate only those users closer than a certain distance, allocate only up to the maximum capacity of the femtos, etc.) This initial allocation can be further refined using genetic algorithms as a numerical optimisation method.
 - *ON creation*: Once the best user-to-femto allocation has been calculated, the Opportunistic Network is created. To do so, new CSG policies have to be redefined to include the new UEs into the femto's service. These new policies are one of the inputs for a new LTE simulation.
- *ON Simulation*: When the configuration and topology of the new ON has been decided, a new simulation is conducted in the LTE kernel. The aim is to gather the new radio KPIs obtained when the new topology is applied.
- *Benchmarking*: Once both simulations have been conducted, a comparison of the KPIs before and after the ON introduction will be made.

2.16.3 Integration in OneFIT architecture

The algorithmic procedure to be developed during this activity can be easily mapped into the OneFIT architecture as shown in Figure 53:

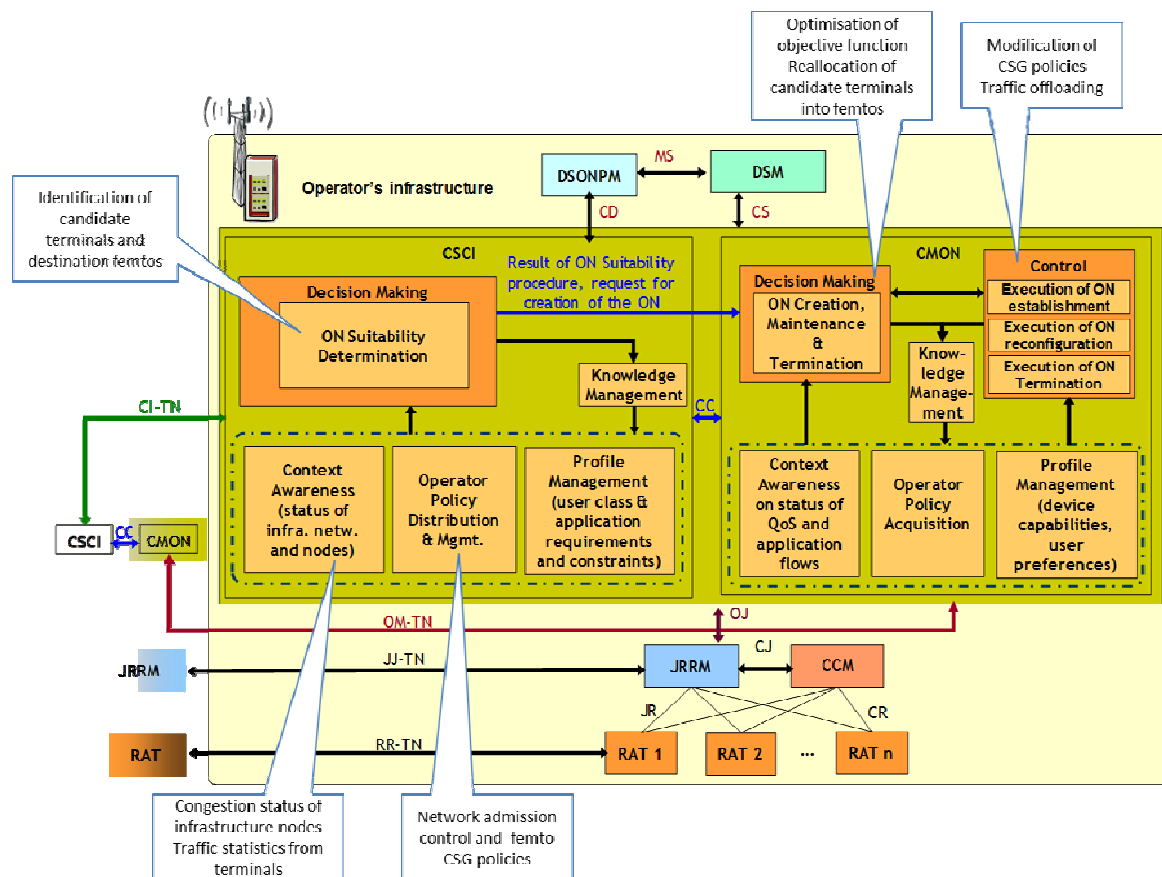


Figure 53 : Mapping of the algorithmic procedure to the OneFIT functional architecture

3. Performance Evaluation

3.1 Evaluation methodology

In order to establish a common framework for conducting the simulation in WP4, the reference model illustrated in Figure 54 is considered. On the left hand side, the proposed algorithm to be evaluated is depicted. Usually, the performance of the proposed algorithm will be shown against another possible solution, which is taken as a reference to assess the potential gains that can be achieved. On the centre, the simulation platform on which the simulations will be run is illustrated. Such a platform will incorporate a simulation of model of various system aspects and will intend to replicate as close as possible to the reality a given scenario and use case. Finally, the performance will be quantified through a number of well-defined metrics, which will be the output of the simulation process. These metrics will be analysed and will enable the derivation of conclusions.

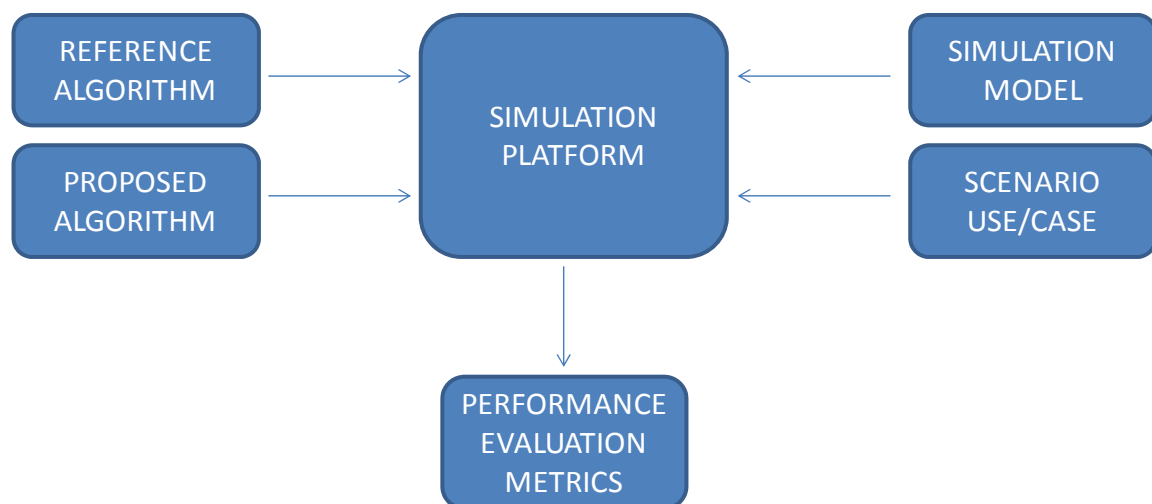


Figure 54:Reference model for simulations

Running simulations is usually a complex task subject to multiple constraints and involves substantial effort. The complexity grows in the case of system level simulations, since the simulation must capture multiple layers of the communication stack (e.g., services/applications, network, access, physical), multiple mobile terminals, multiple base stations, etc. Keeping this in mind and also based on the experience gained in previous projects (e.g., E³), OneFIT partners have adopted an approach that enables the achievement of WP4 objectives while at the same time is claimed to be feasible and pragmatic (in contrast to theoretical formulations, which can later fail due to multiple hurdles in practice). The methodology is sustained on the following considerations:

- Given that diverse simulation platforms across OneFIT consortium are available and that it is intended to exploit in the most efficient way the diverse existing backgrounds and experiences in different platforms, each partner will make its own choice of simulation platform.
- In order to obtain the performance assessment of the proposed algorithms in the OneFIT's scenarios and use/cases, each partner will conduct the necessary adaptations/upgrades/extensions on the internally available simulation platform(s).
- The ultimate goal of WP4 studies is to provide algorithmic solutions for the management of an ON in a comprehensive way. Obviously, the achievable gains of the proposed solution have to be proved, though the provision of reference margin gains (e.g., 60-70% gain) suffices. Therefore, cross-platform calibration and the provision of directly comparable results across simulation platform are not strictly required. This is highly

beneficial for OneFIT, since it is avoided to spend huge efforts in these activities and enables to focus on technical contributions and advances.

- When presenting simulation results, each partner will describe the simulation model implemented in the simulation platform. This will enable the rest of partners to assess the conditions on which the algorithm has been tested.
- Whenever there is the need to compare results obtained with different simulation platforms, the involved partners will develop specific interactions.
 - A joint analysis will be conducted in order to assess at what extent the differences in the simulation models (e.g., different propagation models, different traffic models) may have an influence in the results.
 - In those cases where it is felt that the differences on the simulation model might lead to different conclusions, specific and additional simulation work will be conducted in order to reach confident conclusions.
- Partners will be open to receive suggestions to conduct further simulations from others partners and will support them at the possible extent. This can be particularly useful in the case that the capabilities implemented in one partner's simulation platform are particularly suitable to test and evaluate a solution proposed by a different partner.

3.1.1 Simulator platform features

As it will be detailed in the different subsections, the platforms used for the evaluation of the proposed algorithms have a number of different capabilities and modelling features in accordance with the specific objectives of each evaluation. To have a global perspective about the used simulator platforms and corresponding modelled features for the different algorithms, a comparison is presented in Table 2, which allows identifying the commonalities and differences among them.

3.2 Probability on Suitability for direct device-to-device (D2D) communication

3.2.1 Performance evaluation planning

3.2.1.1 Metrics to illustrate the performance of the algorithm

This section evaluates the probability of having a direct connection to the communication partner for the OneFIT scenario on direct device-to-device communication in dependency of the

- Distribution and density of users
- Range/coverage of direct device-to-device interface

3.2.1.2 Benchmark references

There are no direct benchmark references.

3.2.1.3 Evaluation platform and model

The probability of having a direct device-to-device communication was calculated with a java based "D2D-Link-probability-simulator". In this more business case related evaluation, users are placed randomly on a playground or more concentrated around hot spots with a specified size, also called "Area of Interest" (AOI). Further on, a range of the direct interface between the devices has to be specified.

Table 2: Comparison of evaluation platforms features

Simulators (per task) / Modelling features	Spatial distribution of nodes	Node mobility	Traffic generation model	Propagation model	Interference model	Control of QoS requirements	Handover	Spectrum occupancy model	Multiple hops between nodes	C4MS Signalling
Probability on Suitability for direct device-to-device (D2D) communication and for the coverage extension scenario	X	X		X			X		X	
Fittingness Factor based spectrum selection			X		X	X	X	X		X
Machine Learning based Knowledge Acquisition on Spectrum Usage	X	X	X	X	X	X	X	X		
Techniques for Aggregation of Available Spectrum Bands/Fragments	X	X	X	X	X	X	X	X		
Algorithm on knowledge-based suitability determination and selection of nodes and routes	X	X	X	X			X		X	
QoS and Spectrum-aware routing techniques	X	X	X	X	X	X		X	X	
Techniques for Network Reconfiguration – topology Design				X	X	X				
Application cognitive multi-path routing in wireless mesh networks	X		X		X	X			X	X
UE-to-UE Trusted Direct Path	X					X		X		X
Content conditioning and distributed storage virtualization/aggregation for context driven media delivery	X	X				X	X		X	
Capacity Extension through Femto-cells	X	X	X	X			X			
Support activity to validate ON algorithms on an offloading-oriented real-deployment testbed	X			X	X	X				

3.2.2 Performance evaluation results

3.2.2.1 Evaluation of probability of a direct D2D communication

A direct device-to-device communication can only be established if the two communication devices are in range of each other.

In a first simulation, it was assumed that two users A and B which have been placed randomly on a large playground (20 km * 20 km) want to communicate with each other. If the distance between the two users is smaller than the range of the direct wireless interface, then a direct device-to-device communication is possible, else the session must be made via the infrastructure network. When the

users are distributed randomly in the area, the probability of having a direct interface is very low (see Figure 55, line at the bottom): It is 0,01% if the wireless interface has a range of 100m, 0,05% for a range of 250m and 0,76% for a range of 1000m. In many cases however, the people are not distributed randomly but in certain cases geographically located close to each other, e.g. employees communicating with other employees in the same building or students communicating with other students on the same campus. Therefore, an “Area of Interest” (AOI) was introduced and each user is located with a certain probability (e.g. 10%, 25%, 50%) in that AOI. Figure 55 shows the probability of having a direct connection for a small AOI with a size of 50m * 50m (e.g. office building) and a large AOI with a size of 500m * 500m (e.g. a campus).

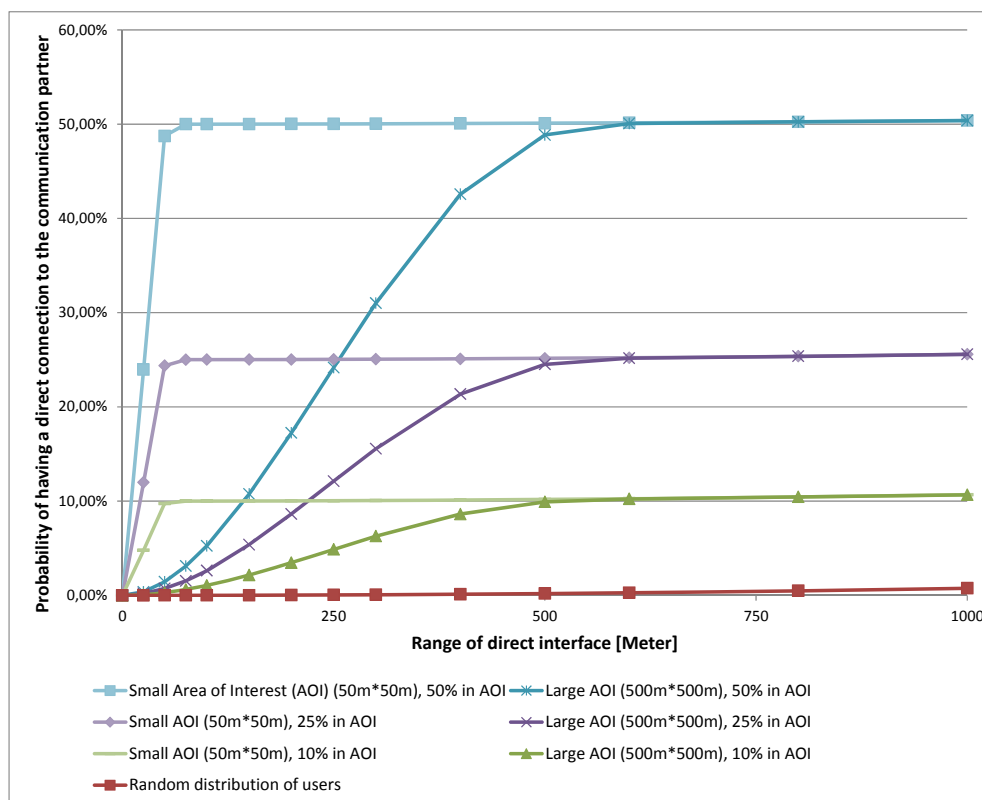


Figure 55: Probability of having a direct connection to the communication partner

3.2.2.2 Evaluation of ON duration with moving users

While an ON is assumed to be stable if the users are not moving, the duration of an ON is limited when the users are moving. Therefore the average duration of a device-to-device connection has been measured with the ONE simulator[11] for different user speeds.

If the wireless interface for example has a range of 100 m and the users average speed is about 0,1 km/h, then the device-to-device connection can last for more than hour (see Figure 56). If the users are moving with 3 km/h, then one device-to-device connection will in average last only 3 minutes and with 6 km/h, it will last only 90 seconds. In order to have a stable ON also for moving users, the ON should include not only one supporting user but connect to additional supporting users if available. Then the connectivity can also be maintained even if one user leaves the area due to his mobility.

3.2.3 Conclusions

As shown in Figure 55, the probability for direct connectivity largely depends on the probability of the users being in the same “Area of Interest” (AOI) and if the range of the wireless interface is around the size of the AOI or larger. Further on, as shown in Figure 56, an ON can be maintained for

a long time if the users are not moving but the possible lifetime of an ON decreases with the velocity of the users.

An infrastructure supported device-to-device communication is mainly attractive in places with many users and local communication needs, e.g. in a household, on a campus, an office building, during a sports event or a group of people being on travel. However, in several of these cases, the traffic can be offloaded via local hot spot access points, so the infrastructure supported device-to-device communication is mainly attractive if such local hotspots do not exist or do not provide a sufficient QoS.

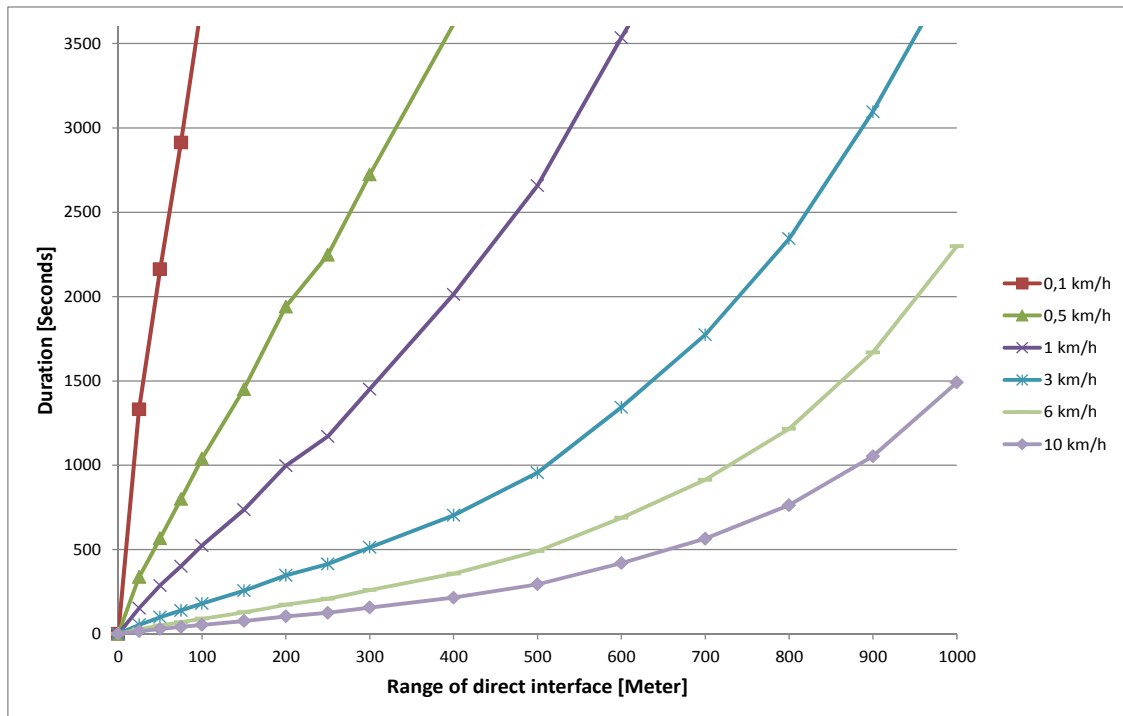


Figure 56: Average duration of a direct connection between two moving nodes

3.3 Probability of suitability for the coverage extension scenario

3.3.1 Performance evaluation planning

3.3.1.1 Metrics to illustrate the performance of the algorithm

This section evaluates the probability of solving an out of cellular coverage scenario with an opportunistic coverage extension in dependency of the

- density of users supporting opportunistic networking in the area
- coverage range of the direct device-to-device radio interface

3.3.1.2 Benchmark references

There are no direct benchmark references.

3.3.1.3 Evaluation platform and model

The probability of solving out of cellular coverage cases with an opportunistic coverage extension was verified with the “D2D-Link-probability-simulator” described in section 3.2 and complemented with further studies using an extended “Opportunistic Network Environment” (ONE)-Simulator[11]. The ONE-Simulator is originally designed for simulations of Delay Tolerant Networks (DTN) and combines movement modelling, routing simulation, visualization and reporting in one tool.

The ONE simulator has been extended to include also cellular networks. Base stations can be positioned at pre-defined positions and the coverage of each base station can also be configured. Each mobile node being in the coverage of the cellular network will be served by one base station. Handovers between cells are also supported, e.g. when the mobile node moves out of coverage of the currently serving cell.

Figure 57 shows a screenshot of the extended ONE-simulator, where one area between 4 infrastructures cells (e.g. LTE cells) has no cellular coverage. If one device moves into that area, then it is evaluated if a direct device-to-device link to another device is possible to provide a coverage extension. Such a case is shown in Figure 57, where UE 31 is out of cellular coverage. A direct link is created with UE6 which is in coverage of Base Station BS0 and thus, connectivity can still be provided to UE31.

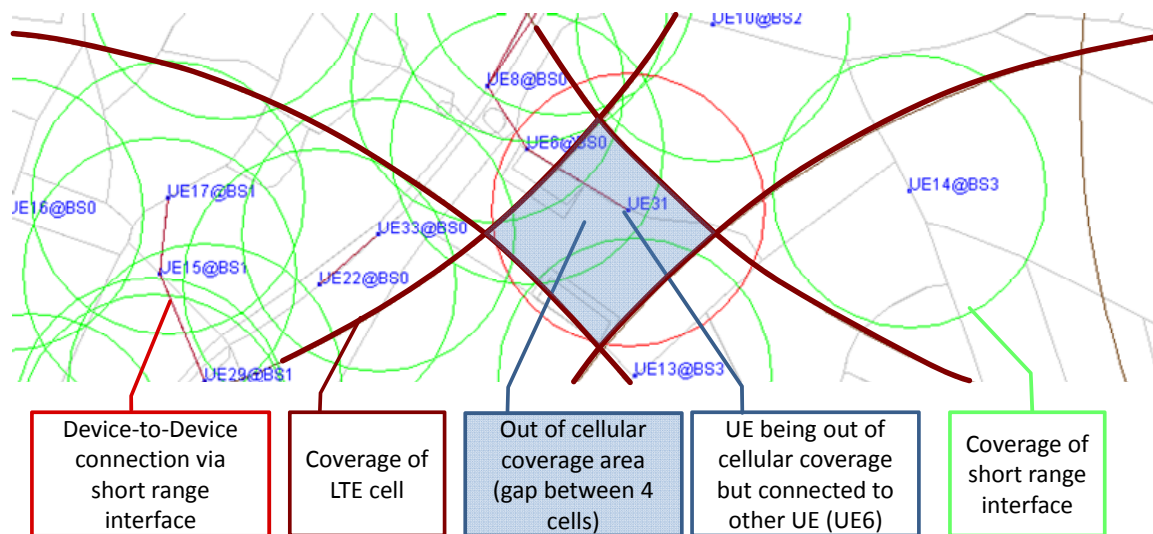


Figure 57: Simulation of the coverage extension for an out of direct coverage scenario

3.3.2 Performance evaluation results

In the opportunistic coverage extension scenario as well as in the scenario on supporting devices having radio access technologies not supported by the infrastructure, a supporting node providing the relaying service towards the infrastructure must be in range of the device which is not directly served by the infrastructure. Figure 58 shows how the probability of having at least one supporting node in range depends on the range of the direct interface and how it increases with the number of users per square kilometre.

The result in Figure 59 shows the number of out of coverage events per hour in dependency of the range of the direct wireless device-to-device interface and in dependency of the user density. The figure shows – as expected – that the probability of solving an out of coverage situation increases when the number of supporting users in that area increases.

For example, with 5 users/km², about 50% of the out of coverage cases can be solved with an ON if the range of the direct interface is about 220m. Having 10 users/km², then 50% of these cases can be solved with an ON if the direct interfaces range is about 160m and with 20 users/km², 50% of these cases can be solved with an ON if the range of the direct interface is only about 120m.

3.3.3 Conclusions

Important scenarios for opportunistic networking are also those cases where a user can not directly access the infrastructure. Two example cases are when a user gets out of the direct coverage of the infrastructure or when the user has a device which does not support the radio access technologies provided by the network.

The solution for these scenarios is by establishing an opportunistic network with a so called “supporting device” in the neighbourhood which then relays the traffic to the infrastructure. This study has presented the probability of finding such a supporting device in dependency of the range of the direct interface and in dependency of the supporting device density.

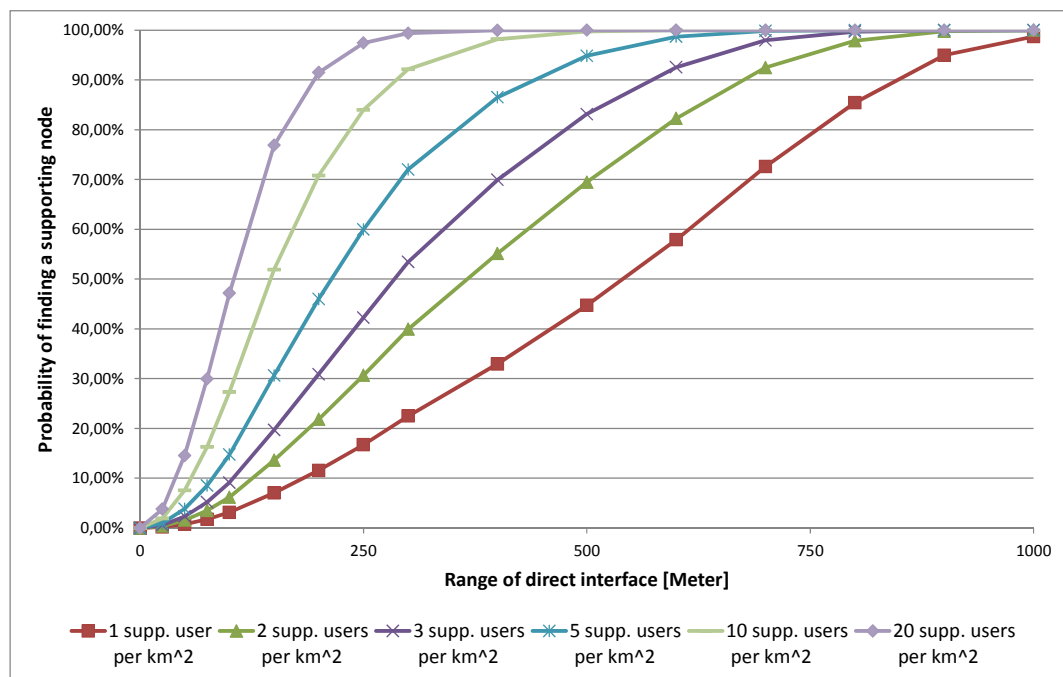


Figure 58: Probability of finding a supporting node for opportunistic networking

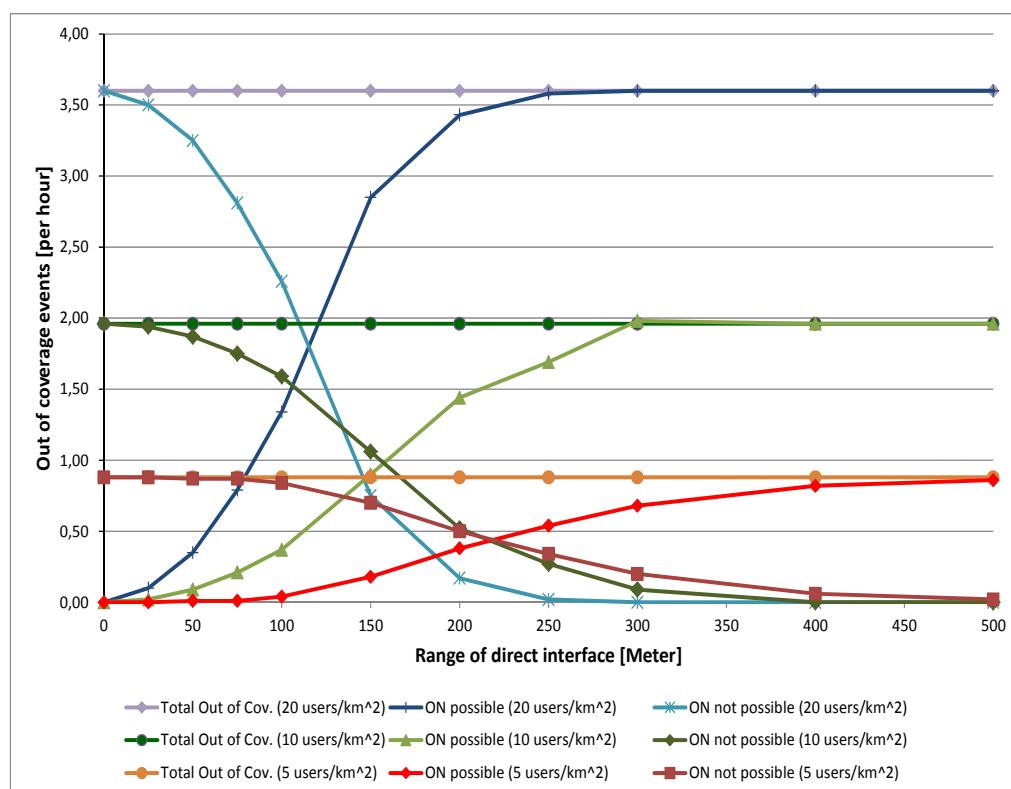


Figure 59: Probability of solving a case of being out of cellular coverage with an opportunistic network

3.4 Modular decision flow approach for selecting frequency, bandwidth and radio access technique for ONs

3.4.1 Performance evaluation planning

3.4.1.1 Metrics to illustrate the performance of the algorithm

The dependency of the output of the decision flow (RAT, spectrum band and bandwidth) to certain input parameters e.g. link length and service class (including application bit rate) will be evaluated. The bandwidth resource usage in each band will be investigated for voice, browsing, and streaming users. In addition, the evaluation of the effect of switching delay to average user capacity on maintenance phase will be carried out.

3.4.1.2 Benchmark references

There are no direct benchmark references for the complete framework in which to compare the results.

3.4.1.3 Evaluation platform and model

The performance evaluation for modular decision flow is carried out by using MATLAB simulation tool. Three different traffic types namely voice, streaming and web browsing are considered. The required minimum bit rates for voice, browsing and streaming users to maintain the required QoS level are 60 kbps, 13 kbps, and 384 kbps respectively [12].

We run the simulations over five TV bands which each have 8 MHz bandwidth, one 2.4 GHz band with 20 MHz bandwidth, one IMT band with 20 MHz bandwidth, and one 60 GHz band with 100 MHz bandwidth. Objective function weights $\omega_1, \omega_2, \omega_3$ are selected between [0 1] depend on the used application. For instance, operator preferences and spectrum availability are weighted more for browsing users and throughput for voice and streaming users.

Single carrier frequency division multiple access(SC-FDMA) is considered. For TV, IMT spectrum bands entire spectrum bandwidth is represented with subcarriers who have spectrum spacing of 15 kHz. 20 MHz band contains 100 resource blocks (RB) and each resource block is formed from 12 subcarriers and duration in time domain is 0.5 ms [13]. Since we consider uplink traffic only, reserved resource blocks for one user are assumed to be contiguous. For 2.4 GHz band we consider 802.11a where subcarrier spacing is 312.5 kHz and for 60 GHz band we consider 802.15.3c where subcarrier spacing is 1.5625 MHz [14]. The assigned number of subcarrier and RB varies and depends on the used application and required minimum bit rate.

3.4.2 Performance evaluation results

On these simulations we assume user to suffer from lack of coverage or capacity and their data need to be connected to the nearest or least congested BS. The algorithm is employed when a new link needs to be established in the creation or maintenance phase or a new spectrum band and RAT needs to be selected in maintenance phase due to changes in spectrum band utility. In the simulations link lengths between user pairs is varied between 3 and 60 meters and stations move with the speed of 2,78 m/s, 1.11 m/s or are stationary.

For Figure 60, Figure 61, and Figure 62 we have run simulations for 30 ON users. Three data types are used for evaluations namely, voice, web browsing and streaming. Here the number of users per data type is 10. Ten users are stationary, ten move with velocity 1.11 m/s and ten with velocity 2.78 m/s. In Figure 60 and Figure 61 the number of users per band and RAT is represented for each data type respectively in the dependency of link length. For example, when link length is 30 m the TV band is allocated for 6 voice users, 3 browsing user, and 4 streaming users; IMT band is allocated for 4 voice, one browsing user and 6 streaming user; LTE is used for 6 voice and streaming users and 3 browsing users; LTE-A for 4 voice and streaming user and 1 browsing user; and 3 browsing users use

2.4 GHz band and 802.11a. For browsing users the 2.4 GHz band is selected mostly at short link lengths due to the browsing users less demanding bit rate requirements. Selected band and RAT depends heavily on link length. From Figure 60 and Figure 61 it can be seen that at short link lengths for voice and streaming users the selected band is mostly 60 GHz band and RAT 802.15.3c. This is due to the good channel capacity that 60 GHz/802.15.3c provides. As the link length increases the 60 GHz band becomes unsuitable due to notably large free space loss, and relatively high molecular absorption by oxygen[15]. The 60 GHz band is best suited for short range, low mobility, and indoor communication. Transmission power constraint restricts the use of TV band in longer transmission ranges as the acceptable transmission power level for secondary users in the TV band is 50 mW. Due to the earlier mentioned problems with TV and 60 GHz bands, the IMT band is selected when transmission range is high. In Figure 62, the occupancy level of each band is presented before and after ON creation. In this simulation the occupancy at the beginning is zero. For example when the link length is 30 m, 22 % of TV band is occupied after ON creation. For 2.4 GHz band occupancy is 10 % and for IMT band 41 %.

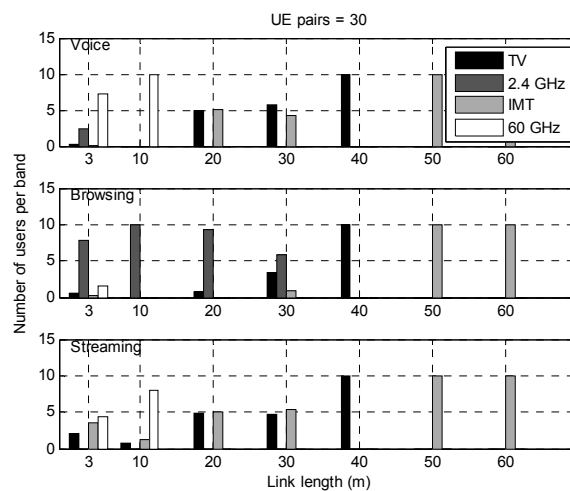


Figure 60: Number of selected Bands per data type

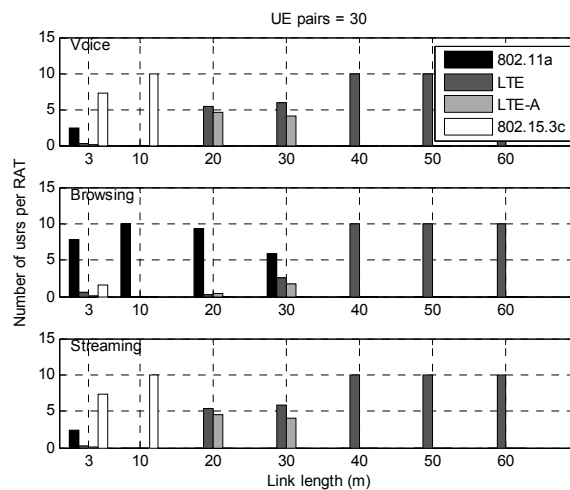


Figure 61: Number of selected RATs per data type

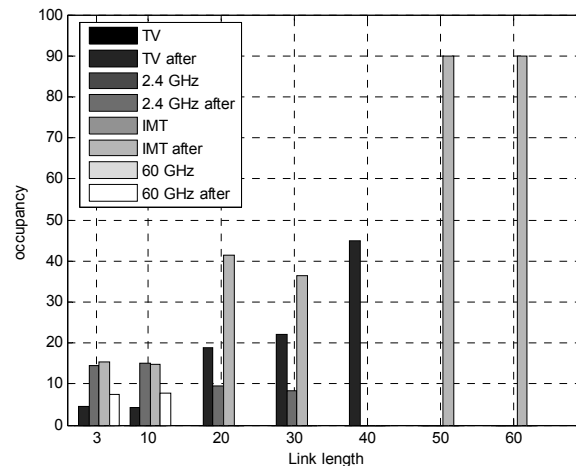


Figure 62: Bands' occupancy levels

When other users appear in the spectrum band algorithm is executed to select new spectrum and RAT for ON users if necessary. When selecting new band and RAT, a transient transmission break will occur, causing delay and performance degradation to ON users. In this subsection we evaluate the modular decision flow approach performance during ON operation. This is done by evaluating the effect of switching delay to average user capacity. Here we consider ON operation where switching delay and delays caused by lack of resources are taken into account. In this simulation, we use exponential distributed interarrivals to model other than ON users' activity. These other users are users who don't participate ON and they can be either primary users (like in TV band) or other non-licensed users like users in 2.4 GHz band or other licensed users in the operators own band (IMT). We exploit the birth death process with death rate α and birth rate β which are uniformly distributed between 0.1 and 0.5. To calculate the average capacity per user we use a normalized capacity model introduced in [16]. For simplicity, perfect sensing is assumed and thus we can set false alarm and detection error probabilities to zero. Thus expected transmission time without switching is $1/\beta$. And switching delay is 1.5 s. ρ is sensing efficiency which depends on the used sensing technique. The link length varies randomly between 1 m to 100 m.

Figure 63 shows bandwidth resource usage in each band for 20 voice users, 20 browsing users, and 20 streaming users when link lengths varies randomly between 3 - 40 m. The results demonstrate that streaming users' reserve most of the available spectrum in IMT and TV band where good channel capacity is expected and browsing users use spectrum mostly from 2.4 GHz band leaving other resources for more bit rate demanding applications. The spots where 60 GHz band is limited refer to situations where range between two nodes is too high and 60 GHz band is not suitable due to poor channel conditions.

Figure 64 shows the average user capacity for each data type function of number of users. The results demonstrate that as the number of ON users increases the average bit rate of each data type decreases because increasing amount of users has to share the same amount of available spectrum causing more often switching delay and transmission break due to lack of resources. The increased transmission range also decreases the average bit rate since bands like 60 GHz are not able to be employed leaving more users to fewer spectrum bands and to RATs which are not able to provide as high bit rates.

3.4.3 Conclusions

In this section we have evaluated modular decision flow approach for spectrum and RAT selection. The proposed decision flow selects band and RAT for one or several ON links and ensures fair operation for whole ON and adequate quality of service for each user. The algorithm is employed when a new link needs to be established in the creation or maintenance phase or when a new

spectrum band and RAT needs to be selected in the maintenance phase. Modular decision flow approach is suitable for e.g. coverage and capacity extension scenarios. Most probably it is suitable for other scenarios also but those haven't been studied here.

The results show that for less data rate demanding applications such as web browsing 2.4 GHz band and 802.11a RAT are selected more often. Results also demonstrate that as the transmission range increases the selected band is IMT and RAT LTE or LTE-A for guaranteeing proper QoS for ON users.

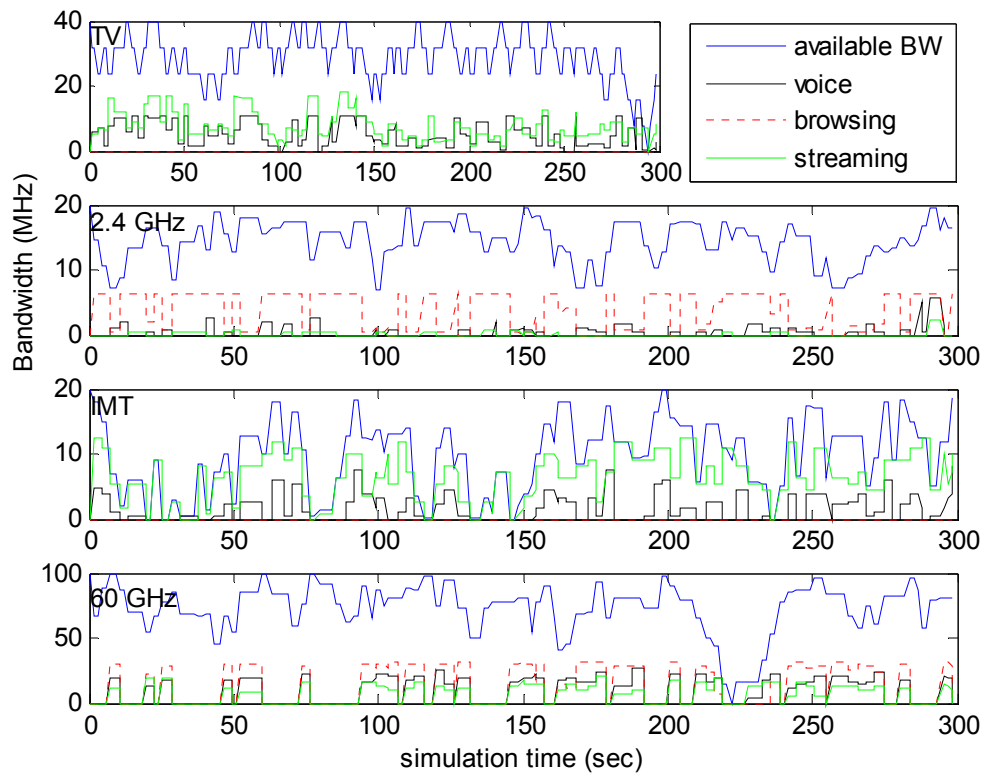


Figure 63: Bandwidth usage for voice, streaming and browsing users

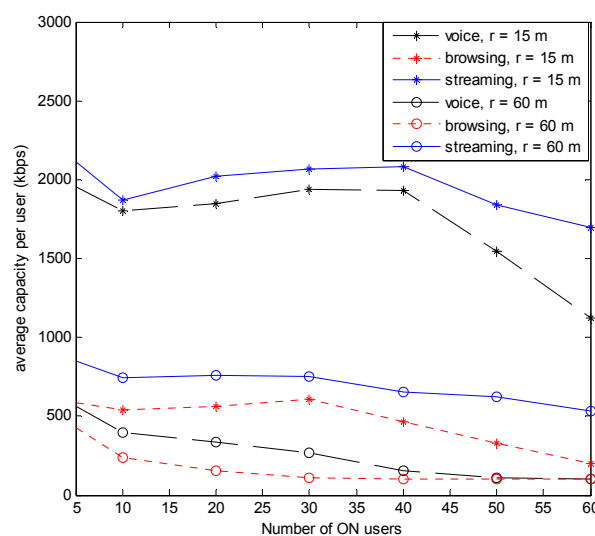


Figure 64: Average capacity per user

3.5 Fittingness-factor based spectrum selection

3.5.1 Performance evaluation planning

3.5.1.1 Metrics to illustrate the performance of the algorithm

Performance evaluation is based on the following metrics, which try to reflect on the one hand the QoS offered to the applications in the ON and on the other hand the efficiency in the resource usage:

- Dissatisfaction probability of the applications in the ON: Probability that the achieved bit rate in the ON radio link is below the requirements. It is given by:

$$Dissf = \frac{\sum_k Nb_Dissatisfied_Links(k)}{\sum_k Nb_Active_Links(k)} \quad (89)$$

where $Nb_Active_Links(k)$ and $Nb_Dissatisfied_Links(k)$ respectively denote the number of active links and the number of dissatisfied links at a given time instant k (i.e. those experiencing a bit-rate $R(l,p,k)$ below the requirement $R_{req,l}$).

- Spectrum HO rate: Average number of SpHO (decision to change the spectrum pool to be used in the ON radio link) per unit of time per ON radio link
- Measurement report signalling requirements: It is measured as the number of reported bits per second transmitted by context awareness modules in charge of providing measurements to the KD.

3.5.1.2 Benchmark references

The following two reference approaches are considered for comparison:

- Random selection algorithm (*Rand*): It allocates a pool randomly among the available ones
- Upper performance bound (optimum selection - *Optim*): It assumes that all the existing allocations in the ON are ideally and instantaneously changed to maximize the number of transmitted bits and minimise the dissatisfaction probability

3.5.1.3 Evaluation platform and model

The algorithm is being evaluated by means of system-level simulations using a C++ ad-hoc simulator. The main purpose of the simulator is to analyse the influence of the spectrum selection over the performance seen by the ON links. In that respect, the most relevant features to be modelled are the traffic generation, the interference seen by the different links in each band, the handovers and the control of the QoS requirements. It is worth mentioning that propagation is not explicitly modelled since it is already captured in the value of the available bit rate that each link can achieve in each specific band depending also on the interference pattern. Based on this, the considered scenario is characterised by the following:

- Traffic characterisation: Two types of radio links $L=2$ are considered in the scenario. The l -th link generates sessions with arrival rate λ_l and constant session duration $T_{req,l}$. Link #1 is associated to low-data-rate sessions ($R_{req,1}=64Kbps$, $T_{req,1}=2min$) while link #2 is associated to high-data-rate sessions ($R_{req,2}=1Mbps$, $T_{req,2}=20min$). The total offered load $\lambda_1 \cdot T_{req,1} \cdot R_{req,1} + \lambda_2 \cdot T_{req,2} \cdot R_{req,2}$ is varied in the different simulations.
- Spectrum and interference characterisation: There are a total of $P=4$ spectrum pools. The available bandwidth at each pool is $BW_1=BW_2=0.4MHz$ and $BW_3=BW_4=1.2MHz$. A heterogeneous interference situation is considered in which the total noise and interference

power spectral density I_p experienced in each pool $p \in \{1..P\}$ follows a two-state discrete time Markov chain jumping between a state of low interference $I_0(p)$ and a state of high interference $I_1(p)$. In the considered case, pools #1 and #2 are always in state $I_0(p)$ while pools #3 and #4 alternate between $I_0(p)$ and $I_1(p)$ randomly with transition probabilities for pool #3 $P_{10}=55.5 \cdot 10^{-5}$ (i.e. probability of moving from state I_1 to I_0 in a simulation step of 1s) and $P_{01}=3.7 \cdot 10^{-5}$ (i.e. probability of moving from state I_0 to I_1) and for pool #4 $P_{10}=9.25 \cdot 10^{-5}$, $P_{01}=1.32 \cdot 10^{-5}$. Based on these probabilities, the average duration of the high interference state is 0.5h for pool #3 and 3h for pool #4 while the average duration of the low interference state is 7.5h for pool #3 and 21h for pool #4. With this configuration, the achievable bit-rate by one link in pools 1 and 2 is $R(I,1)=R(I,2)=512\text{Kbps}$, while for pools 3 and 4, it alternates between $R(I,3)=R(I,4)=1536\text{Kbps}$ for the $I_0(p)$ state, and $R(I,3)=R(I,4)=96\text{Kbps}$ for the $I_1(p)$ state. The interference evolves independently in each pool and this evolution is independent of the traffic in the radio links. Furthermore, no mutual interference effects between different pools exist.

The system is observed during a simulation time $\text{Sim_Time}=1000$ days and the simulator operates in steps of 1s. Other simulation parameters are $\xi=5$, $K=1$, $\delta_{1,p}=0.2$, $\delta_{2,p}=0.9$, $\text{Thr_LOW}=0.9$ and $\text{Thr_HIGH}=0.1$.

The simulator has been developed based on C++ starting from scratch. The simulator validation process has consisted in the following steps, addressing first the validation of the individual modules and then the validation of the integrated simulation tool:

- Validation of the traffic generation module: Different tests have been performed for the random arrival process and the session duration process. In each test, the mean interarrival time during the simulation has been computed and it has been checked that it matches the theoretical input value.
- Validation of the interference/spectrum occupancy module: As indicated, the interference in each spectrum pool follows a 2 state Markov process. During the simulations, the average duration in each of the 2 states has been obtained for each spectrum pool. It has been checked that the obtained values match the theoretical values.
- Validation of the implemented algorithms (spectrum selection decision making, spectrum mobility, knowledge manager): Prior to its inclusion in the simulator, the three considered algorithms have been validated under controlled conditions. For that purpose, a given a-priori known input has been introduced, consisting in different values of the fittingness factor for the specific channels, and it has been validated that the output of the algorithms is the expected one according to their behavior.
- Validation of the capture of statistics to be stored in the knowledge database: The evolution of the interference in the different spectrum pools has been observed for a sufficiently long time, in the absence of any traffic generation, and the set of statistics stored in the knowledge database has been obtained. It has been checked that the statistics follow the expected behavior (either by checking them against theoretical values or by qualitative observation for those statistics that are not easily theoretically modeled)
- Validation of the integrated simulator: Once the different modules have been individually validated, a global evaluation of the simulation platform has been carried out, in this case including the interactions between the different modules. The validation process here has been based on extensive debugging of the simulator, to make sure that the obtained behavior in each time step corresponds all the time with the expected one based on the specific context conditions in each time.
- Simulator output validation: The simulator provides a number of output statistics related with the performance observed by the different links and the required signaling. The validation in this case has been done qualitatively, since it was not possible to derive an analytical model for the expected results. It has been checked that the output performance

indicators follow the expected trends, and it has been analysed in the debugging that the computation of the indicators was correctly performed.

3.5.2 Performance evaluation results

3.5.2.1 Performance comparison

This section presents the performance evaluation of the different considered strategies, with the target to benchmark the performance of the proposed spectrum management scheme with respect to the reference *Rand* and *Optim* schemes.

Figure 65 plots the total dissatisfaction probability (*Dissf*) as a function of the total offered traffic in bps $\lambda_1 \cdot T_{req,1} \cdot R_{req,1} + \lambda_2 \cdot T_{req,2} \cdot R_{req,2}$. It is assumed for the sake of simplicity that $\lambda_1 \cdot T_{req,1} = \lambda_2 \cdot T_{req,2}$. Notice that since link #1 is always satisfied regardless of the assigned pool (i.e., the bit-rate of link #1 is always above the requirement of 64Kbps), *Dissf* depends only on link #2. For a better understanding of the results, Figure 66 plots the fraction of time that link #2 uses pools #3 or #4 under the rationality that link #2 will be satisfied only when using these pools in the low interference state, while it will be dissatisfied whenever it is allocated pools #1 or #2 or pools #3 or #4 during high interference states.

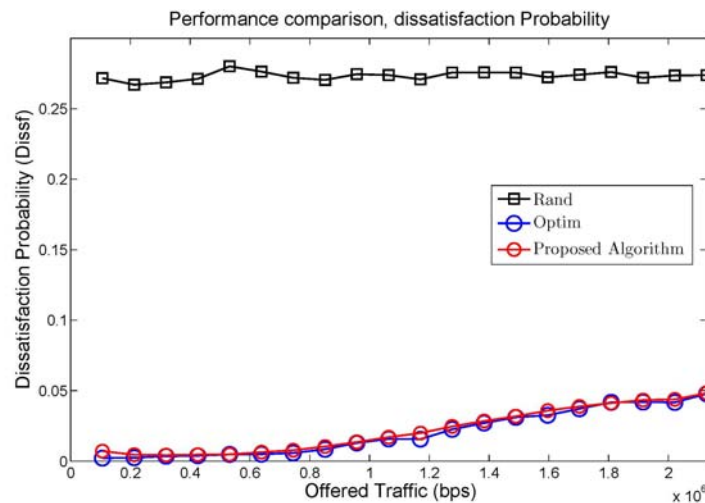


Figure 65: Spectrum selection performance comparison: Total dissatisfaction probability

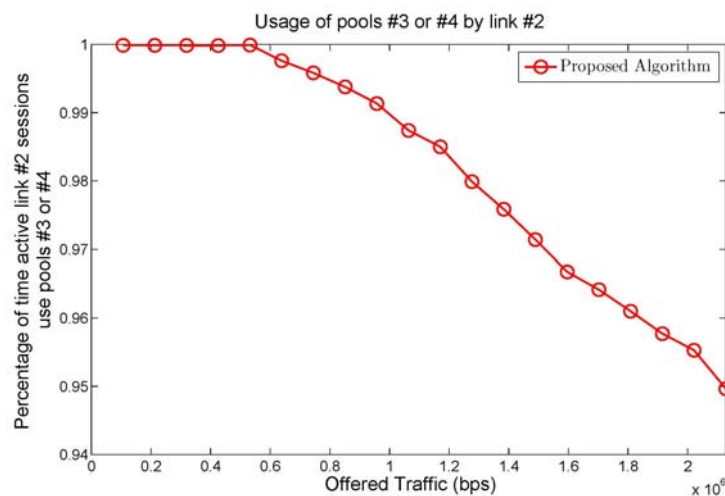


Figure 66: Fraction of time that pools #3 or #4 are allocated to link #2 with the proposed algorithm

As seen in Figure 65, the proposed spectrum selection strategy is able to perform very closely to the upper-bound optimal scheme for all load conditions, and only very small deviations are identified. In turn, the gain observed with respect to the *Rand* scheme (measured as the reduction in dissatisfaction probability) is very significant, ranging from 85% to 100%. The good performance of the proposed algorithm is a consequence of the fact that the proposed algorithm is able to allocate most of the time the pools #3 and #4 to the link #2, as seen in Figure 66, while at the same time pools #1 and #2 are left for the link #1.

A deeper analysis of the results has revealed that the improvements achieved by low loads in terms of dissatisfaction probability are mainly due to the operation of the knowledge manager described in Algorithm 1 that introduces the temporal properties of the evolution of the interference in the different pools when estimating the fittingness factor. This provides the algorithm with a better capability to identify changes than if just the last measured values of fittingness factor were considered. In turn, the improvements for medium and high loads are mainly due to the operation of the spectrum mobility, able to perform the required spectrum handovers to better adjust the spectrum assignment to the current contextual state. Specifically, for high loads it occurs quite often that, at link establishment, the preferred pool is occupied by another link and thus a pool offering lower bit-rate is allocated. In this case, the execution of a spectrum handover after the release of the link occupying the preferred pool allows significantly improving performance.

In the following the impact of varying the interference pattern and the mean holding time of the different links is analysed. Figure 67 presents the comparison in terms of dissatisfaction probability with the proposed approach (denoted as SS+KM+SM since it combines the spectrum selection, the knowledge manager and the spectrum mobility functions) for three interference conditions, namely the reference case that has been considered in the previous study, the case 2 in which all the average durations of the interference patterns have been divided by 4 with respect to the reference case, and the case 3 in which all the average durations have been divided by 8. As a result, cases 2 and 3 correspond to situations with faster variation in the interference. As it can be observed, the obtained performance is not significantly affected by the change in interference, so the proposed algorithm is robust to deal with different interference situations.

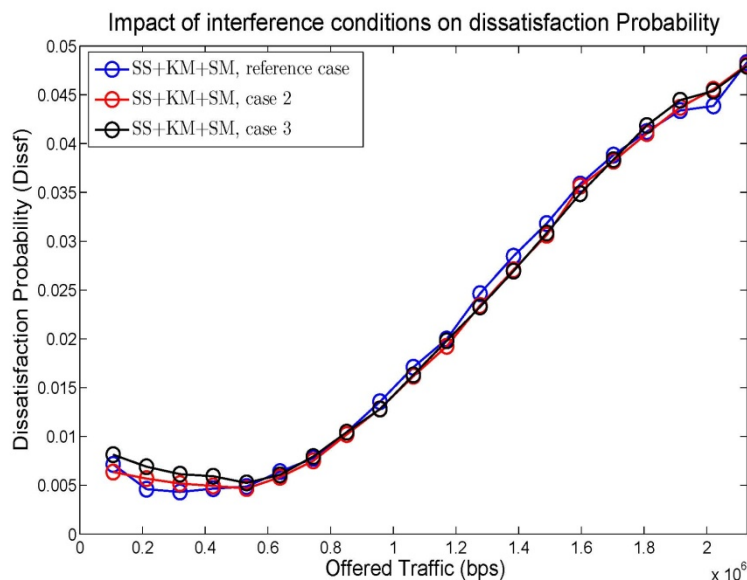


Figure 67: Impact of interference conditions on the total Dissatisfaction Probability

A similar effect is obtained when considering the variation of the session duration, as presented in Figure 68. In this case, the proposed algorithm with the same simulation conditions as in the previous studies (reference case) is compared against the case when the session duration is multiplied by 3 or divided by 3. As it can be observed, the total performance in terms of

dissatisfaction probability as a function of the offered traffic does not change significantly.

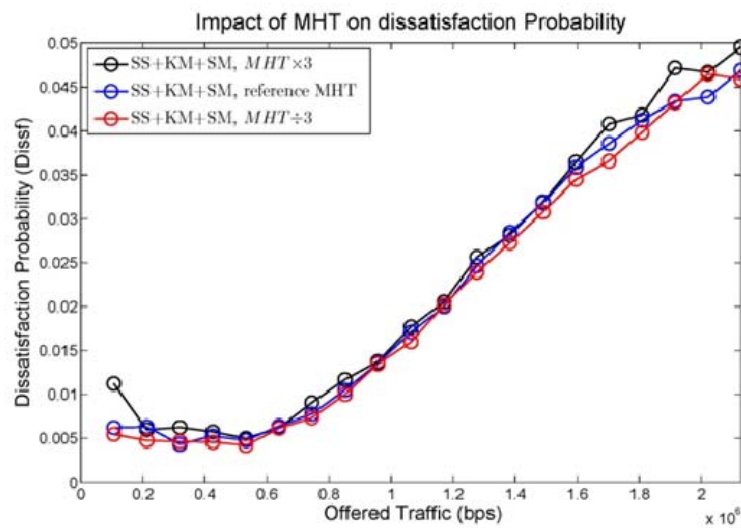


Figure 68: Impact of the session duration on the total Dissatisfaction Probability

3.5.2.2 Practicality considerations

In order to further assess the practicality of the proposed framework, an analysis is performed on the impact of the reconfigurations performed by the spectrum mobility functionality on the radio interface. The impact is evaluated in terms of the amount of SpHO signalling (*Nb. SpHOs/session*). Further studies about the signalling requirements taking into consideration the associated C4MS messages are provided in deliverable D3.3 [7].

Figure 69 plots the amount of SpHO signalling required by the proposed approach for each of the two possible triggers of the spectrum mobility algorithm (i.e. a link release or a change in $F_{l,p}$) as a function of the total offered load. Results show that the proposed strategy requires a low number of SpHOs below 0.25 SpHOs/session for all considered traffic loads. For low traffic loads, the few executed SpHOs are mainly triggered by changes in $F_{l,p}$ values. This is because, at such loads, links are most of the time assigned to their preferred pools (i.e. pools #1 or #2 for link #1 and pools #3 or #4 for link #2). As a result, it is less likely that a better pool is found after a link is released. As traffic load increases, the trigger of spectrum mobility by link releases becomes much more relevant than the trigger by changes in $F_{l,p}$ values and leads to more SpHO executions. This is because at this high traffic load, it is more likely that, at link establishment, a link finds its preferred pools occupied by another link. This result reveals the capability of the algorithm to adapt to different context changes (i.e. interference changes or changes due to the release of other links) depending on the existing load.

In order to evaluate the relevance of the acquisition strategy, an analysis of its impact on the observed system performance versus the signalling cost is presented. The impact on system performance is evaluated in terms of the total dissatisfaction probability (*Dissf*) and the cost in terms of the signalling of the measurement reports sent from context awareness modules to the KD. The computation assumes that each measurement report requires 43 bytes, based on the structures defined in [7].

Figure 70 plots the total dissatisfaction probability (*Dissf*) as a function of the total offered traffic load when the proposed strategy uses an event-triggered acquisition strategy. A periodic acquisition strategy sending measurements reports every $\Delta T(s)$ is also considered for comparison purposes. As far as the periodic acquisition strategy is considered, the results show that, on the one hand, as ΔT increases, the dissatisfaction probability gets worse at low loads but is kept unchanged at high loads (Figure 70). This is because, at low traffic loads, most of the SpHOs are triggered following a change

in $F_{l,p}$ values as previously observed in Figure 69. Consequently, if ΔT is long, these SpHOs are delayed or missed and correspondingly the dissatisfaction level increases. As traffic load increases, SpHOs become mainly triggered by releases of link sessions, which marginalizes the effect of increasing ΔT on the dissatisfaction probability. As far as the event-triggered acquisition strategy is considered, results show that it outperforms the periodic approach from the perspective of dissatisfaction probability.

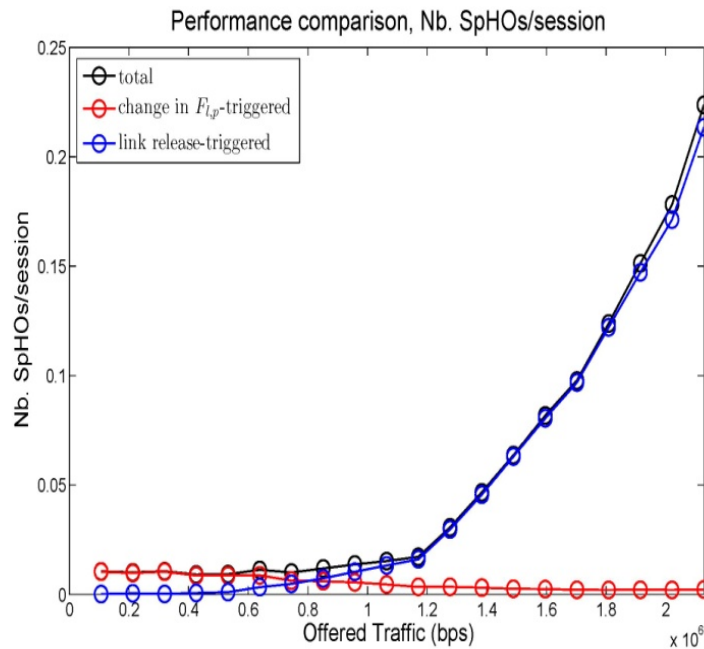


Figure 69: Number of SpHOs/session with the proposed algorithm.

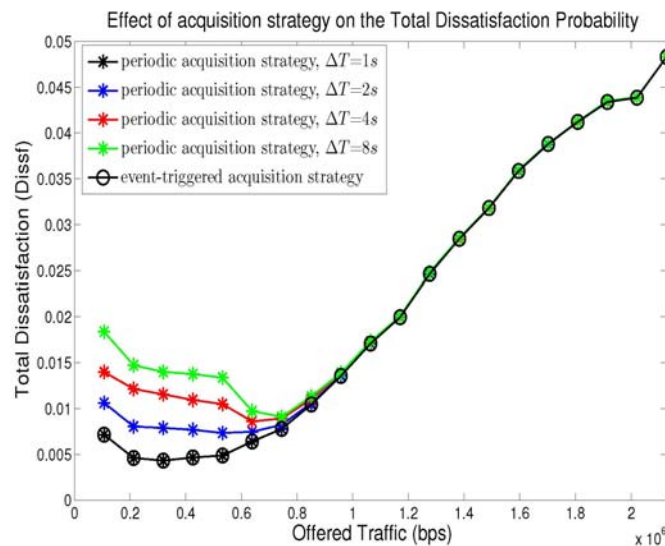


Figure 70: Impact of acquisition strategy in terms of dissatisfaction probability

3.5.3 Conclusions

This section has presented the evaluation of the fitness factor-based spectrum selection algorithm that targets the assignment of an adequate spectrum pool to a set of links between nodes in an ON in accordance with the application requirements associated to each link. The algorithm is supported by a Knowledge Management entity and a Decision-Making entity that includes both the spectrum selection at session initiation and the spectrum mobility to decide on changes in the spectrum assignment. The proposed approach integrates the fitness factor concept that captures

the time-varying suitability of available spectrum resources to different applications. A set of advanced statistics capturing the influence of the dynamic radio environment on the fitness factor are retained in a Knowledge Database and are used by the Knowledge Manager to extract the most relevant knowledge to assist a proactive strategy for both Spectrum Selection and Spectrum Mobility decision-making processes.

The performance evaluation results have shown that the proposed strategy that combines the knowledge manager and the spectrum mobility efficiently exploits the knowledge management support and the spectrum mobility functionality to introduce significant gains (ranging from 85% to 100%) with respect to a random selection and to perform very closely to the upper-bound optimal scheme. This is thanks to the capability of the proposed approach to adapt to contextual changes such as interference changes or modifications due to the release of other links. The strategy has been also evaluated from the perspective of its practicality in terms of the rate of required spectrum handovers, revealing a low rate of handovers particularly for low and medium loads, and from the perspective of the measurements exchange to support the context acquisition. It has been obtained that the strategy can be efficiently supported by an event-triggered context acquisition.

3.6 Machine Learning based Knowledge Acquisition on Spectrum Usage

3.6.1 Performance evaluation planning

3.6.1.1 Metrics to illustrate the performance of the algorithm

The set of actions $\{A_{t,j}\}$ taken by the j^{th} node on all sub-channels represents the spectrum pools at each time t . Indeed, $\{a_{t,j}^i = 1\}$ means that the i^{th} sub channel is not utilized by primary network, while $\{a_{t,j}^i = 0\}$ means that the sub channel is occupied, either by primary network, or other secondary nodes.

The main metric (also the output of the algorithm) is the utilization probability ($p_{t,j}^i$) at each time step t , sub-channel i and AP j . The utilization probability is defined as the probability of the sub-channel to be not utilized by LTE RAN. So, sub-channels with high utilization probability are most likely to be free for opportunistic access by secondary nodes.

The reward model and the utility function are described in the following sections.

3.6.1.2 Benchmark references

In the simulations two benchmark references have been considered:

- For the secondary system: the performance of the proposed algorithm has been evaluated against FSA. According to Gradual Deployment of Carriers (GDC), the FSA module randomly assigns carriers to the node based on predicted demand.
- For the Primary system: the scenario when there are no secondary nodes connected with the co-located cells (no cross-layer interference) had been used as a reference to measure the accuracy of the channel-modeling scheme.

3.6.1.3 Evaluation platform and model

The simulations carried out are based on the Downlink Long Term Evolution (LTE) System Level simulator that has been modified to cope with the given co-existence scenarios. Also, spectrum configuration (optimization) toolbox, with different learning strategies had been added to the simulator.

The considered scenario in the simulation consists of cluster of LTE radio access network (RAN), comprising three sectors eNBs located at the centre of the macro cell, and a layer of 30

opportunistic access, random located nodes overlaid upon the macrocell system, as shown in Figure 71. Two layers are based on the use of multiple access technologies: specifically, orthogonal frequency division multiple access (OFDMA) for the downlink.

Each node interacts with the environment (LTE RAN) with one of the learning strategies as described before, to build a probabilistic model of the spectrum. The expected output of the simulator is the utilization probability ($p_{t,j}^i$) at each time step t , sub-channel i and node j . The utilization probability is defined as the probability of the sub-channel to be not utilized by LTE RAN. So, sub-channels with high utilization probability are most likely to be free for opportunistic access by secondary nodes.

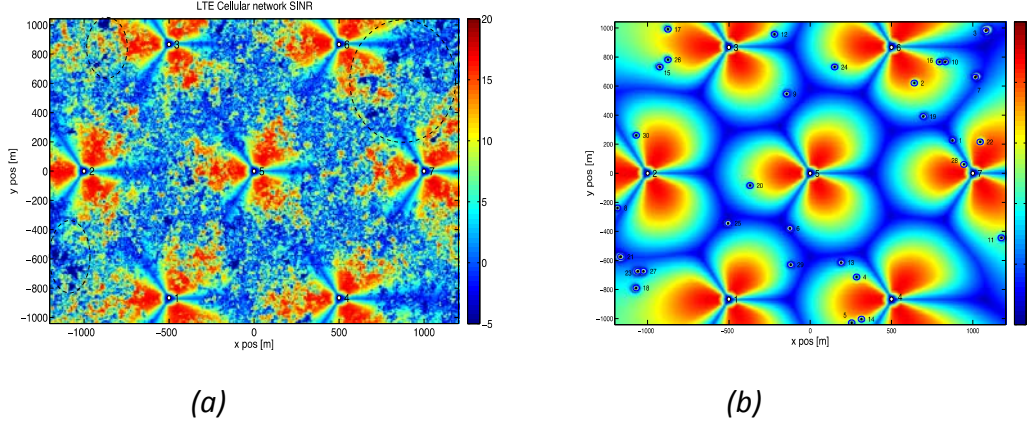


Figure 71: Considered scenario of LTE RAN and FCs co-existence; (a) 'TS36942' pathloss model, urban environment, and shadow fading, (b) 'TS36942' pathloss model, urban environment.

The utility function:

The utility function $(u_{t,j})_A^\delta$ can follow different forms according to the nodes' objective. For example, the utility function of energy saving problem is different than maximizing node capacity problem. Indeed, the target of the learning strategy is to give higher probability for the sub-channels that maximize the stated objective by each node.

For the given scenario problem, the utility function considered in the simulation as follows:

$$(u_{t,j})_A^\delta = 1 - \frac{R_{t,j}^a}{M} \quad (90)$$

where $R_{t,j}^a$ is the reward signal received by the j^{th} node from a successful interaction with the environment, as consequences of selected action a , and M is a normalized parameter. The utility function is bounded by $[0,1]$ and the reward signal is given by means of estimated average SINR ($\hat{\gamma}_j$).

Initial configuration for the RL algorithm:

First, we set up the initial configuration of the optimization toolbox for both RL1 and RL2. For RL1, we considered the following parameters:

- Each node has an initial configuration of strategy $\pi_{0,j} = 0.5$, and propensity of action $\omega_{i,a} = 5$, $\forall i$ and $\forall j$;
- The temperature parameter $\tau = 100$, the recency parameter $\phi = 0.02$, and the experimentation parameter $\varepsilon = 0.98$;

For RL2, we considered the following parameters:

- Each node has an initial configuration of strategy $\pi_{0,j} = 1$, utility average $\hat{u}_{0,j} = 0$, and propensity of action $\omega_{i,a} = 5$, $\forall i$ and $\forall j$;

- The constant step-size parameter $\lambda = 5$, the learning rate $\alpha = 0.8$, and The temperature parameter $\tau = 100$;

3.6.2 Performance evaluation results

Figure 72 shows node number {1} strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$ versus the learning iteration steps, for sub channels {1,5,6,20}. As shown in Figure 72(a), the utilization probability $p_1(t)$ of all sub channels started with the initial configuration $p_1(0) = 0.5$, at time step $t = 0$. As the learning iteration increased, the probability of the sub channels that maximize the objective converged to {1}, while the other sub channels' probabilities turned to {0}. This is due to the changes in the propensity of actions $\{\omega_0, \omega_1\}$ according to the learning strategy RL1, as shown in Figure 72(b).

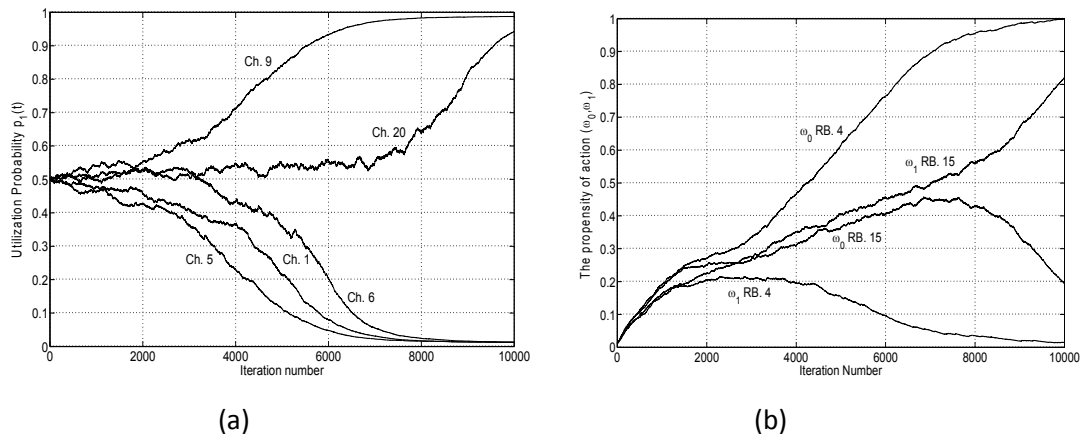


Figure 72: RL1 Node{1} strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$: (a) Utilization probability $p_1(t)$ (b) The propensity of actions $\{\omega_0, \omega_1\}$, versus learning iteration number.

The strategy $\pi_{t,j}$ of taking action $a_1 = \{1\}$ for all sub channels after 5×10^3 and 7×10^3 learning steps is illustrated in Figure 73. As shown, higher probability is assigned to sub channels {9 to 13} and {19 to 24}. These sub channels identified as most likely to be free and can be used for opportunistic access by the secondary nodes. As the iteration steps increased, the nodes acquired better knowledge about the spectrum usage using RL1.

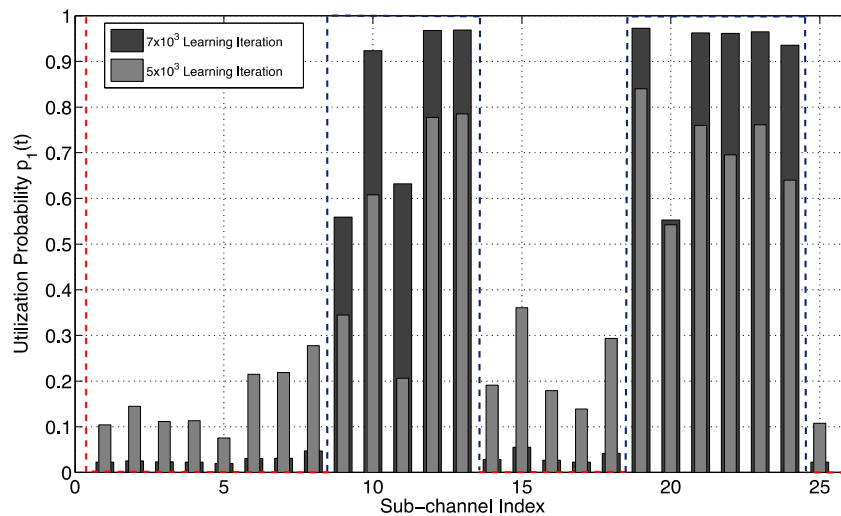


Figure 73: RL1 node{1} strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$, after 5×10^3 and 7×10^3 learning iteration.

As regards to RL2, Figure 74 shows the node strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$ versus the learning iteration steps, for sub channels $\{4,6,15,16,20\}$. The utilization probability $p_1(t)$ of all sub channels started with the initial configuration $p_1(0) = 1$, at time step $t = 0$. As the learning iteration increased, the probability of the sub channels that cause harmful interference will converge to $\{0\}$, while other probabilities didn't change significantly. This is due to the changes in the weights of actions during the learning strategy RL2.

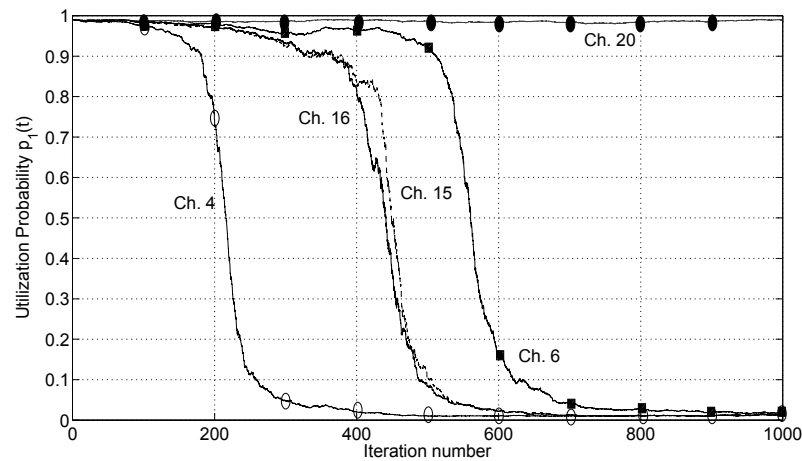


Figure 74: RL2 node $\{1\}$ strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$, Utilization probability $p_1(t)$

Figure 75 shows the strategy $\pi_{t,j}$ of taking action $a_1 = \{1\}$ for all sub channels after 2×10^3 , 4×10^3 , and 10×10^3 learning steps. It is clear that the probability assigned to sub channels $\{1 \text{ to } 8\}$, $\{13 \text{ to } 18\}$ and $\{25\}$ are reduced significantly compared to the remaining channels. These sub channels identified as occupied and may cause harmful interference. As the iteration steps increased, the nodes acquired better knowledge about the spectrum usage.

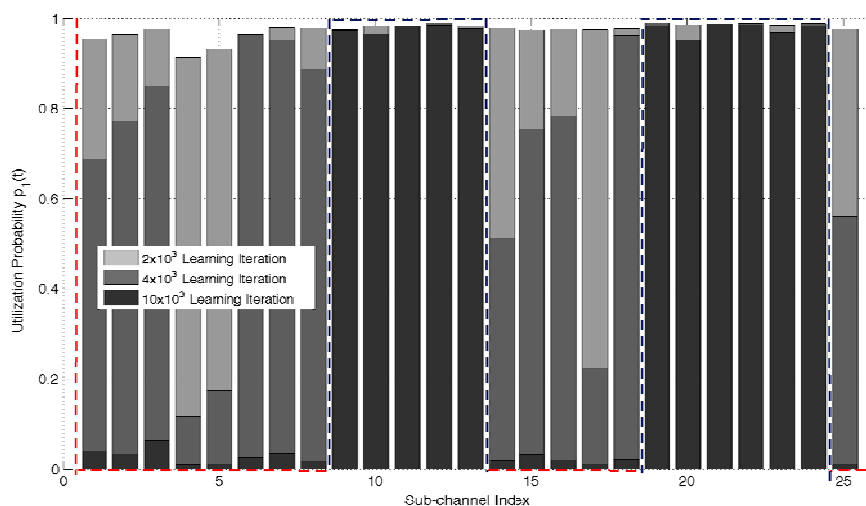


Figure 75: RL2 node $\{1\}$ strategy $\pi_{t,j}$ of selecting action $a_1 = \{1\}$, after 2×10^3 , 4×10^3 and 10×10^3 learning iteration.

The effect of the FCs coexistence with the primary RAN can be shown clearly in fig. 15. Indeed, the degradation in the SINR of the femtocells and macro system could lower the achievable gain in the capacity and reduces the user satisfaction probability in both networks.

In Figure 76, the performance of the proposed algorithm has been evaluated against FSA. According to Gradual Deployment of Carriers (GDC), the FSA module randomly assigns carriers to the FCs based on predicted demand.

However, by adopting the learning strategies, each node should have the capability to sense its environment, triggers the learning algorithm and tune its parameters accordingly, in order to operate under restrictions of avoiding interference to other femtocells and macrocell users at the same time. It can be seen from the simulation results that the proposed scheme not only avoids interference to the neighbouring FCs but also to the primary system.

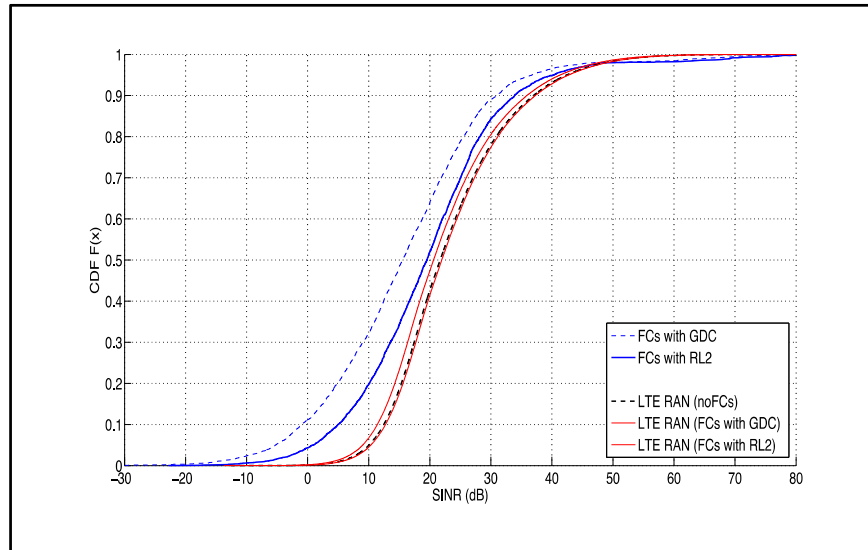


Figure 76: Cumulative distributed function of the SINR, LTE RAN and FCs.

3.6.3 Conclusions

The work proposed is a novel distributed available channel identification algorithm based on machine learning, targeted at modelling the spectrum occupancy and identification of spectrum pools for opportunistic access by secondary network. The secondary nodes do not need any information from the primary system or any neighbouring nodes.

As shown in the simulation results, with time, the algorithm learns by successful interactions with the environment (rather than relying on spectrum usage history) which resources to be used in order to avoid/not cause harmful interference as well as providing a suitable quality of service (QoS). Such intelligent schemes can provide a practical solution to the main challenge of interference in multi layer networks.

3.7 Techniques for Aggregation of Available Spectrum Bands/Fragments

3.7.1 Performance evaluation planning

3.7.1.1 Metrics to illustrate the performance of the algorithm

Since the proposed algorithm aims three objectives, the performance evaluation is based on the following metrics, which try to reflect each objective.

- Total throughput in the ON: total number of bits/s successfully transmitted in the ON radio link
- The number of channel switching : Average number of channel switching (decision to change the spectrum pool to be used in the ON radio link) per unit of time

- The number of bands used for aggregation : Average number of bands for aggregate channel of each radio link

3.7.1.2 Benchmark references

The performance evaluation of the proposed spectrum aggregation algorithm could be categorized two parts: the utility-based multi-objective spectrum aggregation and the adaptive weight setting with the machine learning

For the evaluation of the utility-based spectrum aggregation's performance, the following two reference approaches are considered for performance comparison:

- Random aggregation algorithm: It selects sub-channels randomly among the available sub-channels
- Single objective Aggregation algorithm: It can be implemented by adjusting the weight of each objective.
 - For the weights of three objective, $\{w_1, w_2, w_3\}$: $\{1,0,0\}$, $\{0,1,0\}$, $\{0,0,1\}$

For the evaluation of the adaptable weight setting, the proposed algorithm applying the equal-setting weights but without learning module is exploited for the performance comparison.

3.7.1.3 Evaluation platform and model

The algorithm is being evaluated by means of the Matlab simulations. The scenario is characterised by the following:

- Traffic characterisation: In order to simulate the opportunistic spectrum access, PU traffic modelled through the On/Off process with the unit of a channel of 200kHz width is generated. Since the number of secondary users is variable for the performance evaluation, service time follows a uniform distribution with the mean 5secs. Once finishing the service time of a certain link, the link is terminated and new link appears to request the resource. Each link in the ON is assumed to require 5Mb/s during the service time.
- Spectrum characterisation: It is assumed that 30 MHz is available for 4 different bands. The average spectrum occupancy by primary users is set to 50%.

3.7.2 Performance evaluation results

The proposed algorithm is not scenario specific therefore applicable to all OneFIT scenarios.

The same priority to three different objectives i.e. the weight-vector of multi-objective utility $\{w_1, w_2, w_3\}$ is set as $\{1/3, 1/3, 1/3\}$ for the first stage simulation. Performance evaluations in the following sections compare performance of the random aggregation method (labelled as "Random") with different settings of the weight vector.

Figure 77(a) presents the normalized total throughput experienced by the SUs. It compares the case with equal-weight setting $\{1/3, 1/3, 1/3\}$ against the optimal setting for $\{1,0,0\}$ that allocates the channel with the best quality and thus is optimal from the perspective of throughput. It is observed that the proposed equal-weight setting outperforms Random algorithm and can reach 90% performance of the optimal setting. Figure 77 (b) evaluates the channel switching performance. The algorithm which only considers the remaining idle time through the setting $\{0,1,0\}$ becomes the optimal algorithm for channel switching. The equal-weight setting results in more channel switching but presents better performance than the Random aggregation. Lastly, the number of bands used for spectrum aggregation for the complexity of spectrum aggregation is evaluated. The algorithm which only considers the number of bands through the weight setting $\{0,0,1\}$ is the optimal from the perspective of this performance metric. However, the equal-weight setting achieves a performance close to this optimum.

As the number of users increases, the total throughput also increases. However, when the number of users is over 15, it becomes saturated due to a lack of available spectrum. As the number of resource requests increases, the probability that channels having short remaining idle time are utilized increases and this leads to increase in the channel switching. However, due to increasing competition between users, the amount of spectrum resource allocated to users is reduced. Thus, smaller number of sub-channels is aggregated into an aggregate channel and the number of bands decreases.

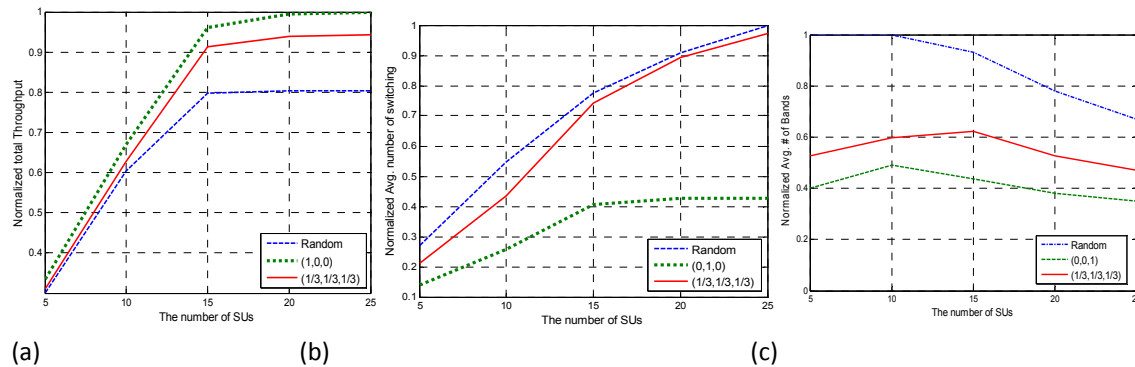


Figure 77: (a) Normalized Total Throughput (b) Normalized number of channel switching (c) Normalized number of Bands used for aggregation

The proposed method for the automated setting of weights relies on pre-set thresholds per objective. Although at the outset system KPIs can be used to determine and set the required performance thresholds, in our simulations as depicted in Figure 78, the average performance of the first observation interval (period 0- T_A) plus a 10% margin is used to set the actual thresholds for the channel switching and the number of bands for aggregation. Since the number of user requesting resource is 15, the threshold for throughput performance is then set as the sum of requested throughputs, i.e. 75Mbps. The equal-weight setting is used to set the initial weight value. During the period T_A to T_B , the number of channel switching is increasing and it is detected at time T_B (actually triggered by adjusting PU's ON/OFF pattern). Then the learning algorithm is run during learning phase i.e. phase T_B - T_C , and the optimal weight vector is obtained. Then, the selected weight vector is used by the spectrum aggregation algorithms at T_C at which point the monitoring phase also begins. While the performance of "No-Learning" from T_C to T_D shows no improvement compared to the performance from T_A to T_B , it is observed that the proposed approach using RL learning does improve the channel switching performance thus it could meet the predefined threshold. Although the corresponding period throughput performance does not show any major changes, the number of bands for aggregation within period T_C - T_D is degraded and shows an increase to a level close to the set threshold. This is because the proposed spectrum aggregation algorithm prefers to select the sub-channels with lower remaining idle time although more sub-channels may be required. The use of more sub-channels lead to increases of the number of bands for aggregation as illustrated in Figure 78. Although the number of bands for aggregation is only selected as the metric for the spectrum aggregation complexity, the performance of number of sub-channels has the similar pattern with the performance of the number of bands for aggregation.

From time T_D to T_E , i.e. during the next monitoring phase, throughput performance is degraded (actually triggered by adjusting channel quality). The learning process is triggered at time T_E and following the new learning phase from T_E and T_F . Then the new optimal weights are used by the proposed spectrum aggregation algorithm. In this case, the obtained improvement in throughput is accompanied by a reduction in number of channel switching as the result of learning process.

The predefined threshold can be changed due to some reasons such as the change of the number of users. The case of change for the predefined threshold is implemented in the simulation. From time T_G to T_H , i.e. during the next monitoring phase, the threshold setting is changed and it is detected

that performance of throughput and the number of bands is degraded at the time T_H . The learning process is triggered the new optimal weight are selected at T_I . While the performance of the number of bands is improved, the number of channel switching is increased. It is analyzed that the proposed aggregation algorithm tries to select the sub-channels of good channel quality although they have less remaining idle time. For all cases illustrated above, it is showed that improvement in the specific performance metrics degraded requires the performance of different metric degrade as the trade-off.

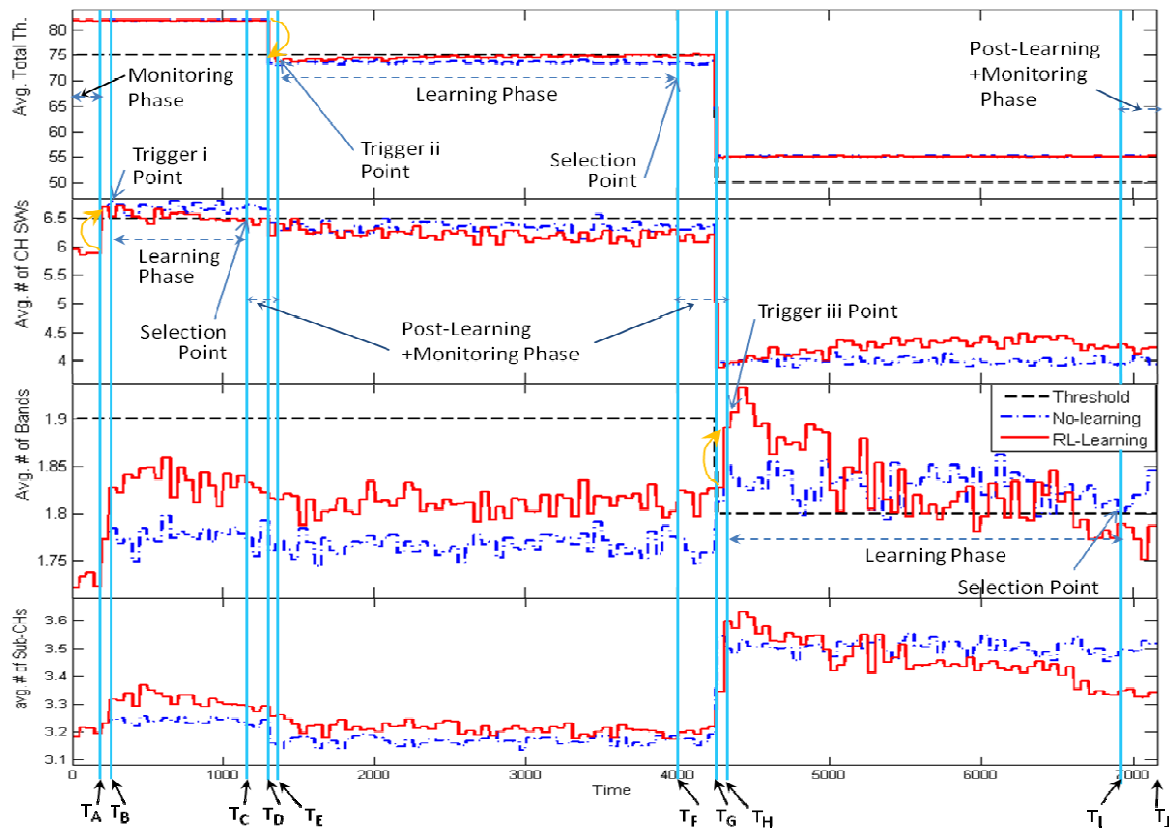


Figure 78: The performance comparison of RL-learning and No-learning approach

3.7.3 Conclusions

In the proposed algorithm, total throughput, the number of channel switching, and the number of bands for aggregate channels have been considered as the performance metrics with respect to the nature of secondary user's spectrum use and aggregation capability. The utility function for three performances is developed as a weighted sum utility function. Since the optimal weights setting can be different depending on the performance metric of interest, a Q-learning approach is used to determine the optimal weights. The proposed approach is shown to be adaptable to changes amongst different objectives of interest. The proposed framework included a learning module allowing for to management of complex interactions and trade-offs between different metrics without manual intervention.

3.8 Algorithm on knowledge-based suitability determination and selection of nodes and routes

3.8.1 Performance evaluation planning

3.8.1.1 Metrics to illustrate the performance of the algorithm

In the following paragraphs, results are presented related to the performance of the proposed algorithm in terms of:

- The load of the infrastructure elements before and after the solution enforcement
- The impact on packet loss
- The impact on message delivery delay
- The impact on energy consumption in BSs and terminals.

3.8.1.2 Benchmark references

For benchmarking, the situation before the solution enforcement is considered (which means how the operator's network responds in congested situations). Also, wherever the impact of mobility is evaluated, for benchmarking reasons, the performance with no mobility is considered.

3.8.1.3 Evaluation platform and model

This section presents results on the performance of the developed capacity extension scheme through the creation of ONs. An agent-based, Java prototype has been developed by using the Java Agent Development Platform (JADE) as described in [10]. JADE has been used for the management functionality and the exchange of messages. Also, an area of 4000m x 4000m is investigated through the Opportunistic Network Environment (ONE) simulator [11]. We have modified it accordingly, in order to include also communication with infrastructure and to integrate our developed Java prototype so as to find paths from terminals located in congested areas to neighboring, non-congested areas. The ONE simulator has been chosen for the experiments due to its inherent capabilities in measuring performance of traditional ONs. Furthermore, the WINNER B5f propagation model [20] was integrated at the customized ONE simulator. The path loss can be estimated through the following equation:

$$PL = 23.5 \cdot \log(d) + 57 + 23 \cdot \log\left(\frac{f}{5}\right) \quad (91)$$

Where d is the distance between the BS and the terminal and f is the frequency in GHz at which the BS operates.

In addition, the Friis formula is exploited in order to estimate the path loss among the terminals of an ON:

$$PL = -27.55 + 20 \cdot \log(f) + 20 \cdot \log(d) \quad (92)$$

Where d is the distance of the terminals and f is the frequency in Hz at which the terminals operate.

3.8.2 Performance evaluation results

Seven infrastructure elements (BSs) cover the aforementioned area –one in the middle and one in each side of the central cell. A hundred and thirty terminals are deployed in the area. All terminals are assumed to be capable of participating in an ON, if the right conditions exist (e.g. their mobility level is relatively low, such as a few m/s, or the policies of the operator allow the formation of further ONs etc.) The majority of the terminals are located in the central BS (BS1) in order to be able to emulate a congestion situation. The following spatial distribution of terminals is considered: 40

terminals in the congested, central cell and 15 in each adjacent cell. Data services are taken into account and rate of message generation is a random variable ranging from 3 to 7 seconds, uniformly distributed, with mean of 5 seconds. Message size is a random variable in the range of 64 to 1024 KB uniformly distributed. Also, the number of terminals that generate traffic in each interval is random as well.

Twenty-seven testcases listed in Table 3 have been evaluated according to the following table. In terms of mobility, the Random Walk mobility model has been used and measurements have been performed for specific moving velocities ranging from stationary (0 m/s) to 2m/s. Mobility level of 0-2 m/s following a Random Walk model has been considered in order to maintain traffic distribution in cells. Figure 79 illustrates the topology as described earlier in the paragraph. Each simulation lasts for 1000 simulated seconds, due to the fact that according to the definition of ONs, ONs are created in a specific place for a limited timeframe in order to serve temporarily the involved users.

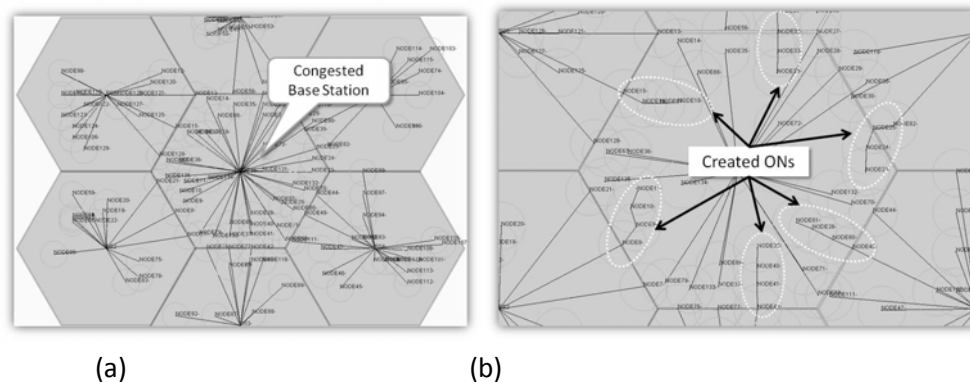


Figure 79: Topology snapshot from ONE (a) before the creation of ONs and (b) after the creation of ONs

Created ONs have an average number of participating nodes ranging from 1 to 3 according to the considered testcase. According to the “tethering” concept, a single terminal can be used in order to serve as many as 5 to 8 users. The “tethering” concept makes possible the connection of nearby users to gain access to the network by connecting to a single terminal and using its connection (as long as its owner permits it of course). In our simulations though, relatively smaller ONs are considered.

In the following paragraphs, results are presented related to the performance of the proposed scheme in terms of the load of the infrastructure elements before and after the solution enforcement, the impact on packet loss, delay and energy consumption in BSs and terminals. Initially, BS1 is considered congested, while neighboring BSs are considered as not congested, so traffic from terminals in the congested area can flow through intermediate users into the non-congested BSs. Figure 80a provides the trend of the load in the congested BS before and after the solution enforcement while b provides the trend of the load in a non-congested BS which acquired traffic. In both figures, the horizontal axis shows the simulated time in seconds while the vertical axis provides the average load in Kbps when 18, 12 or 6 terminals switch to ON, for all capacity and mobility levels. On the other hand, the six neighboring BSs acquire the traffic of an average of 1 to 3 terminals each time, so impact on their load is not very significant as suggested from Figure 80b. Figure 80a and b show the impact on the load when 18, 12, 6 terminals switch to ON, since in all other testcases where capacity and mobility level are changing, the impact on the load remains the same. This is because even if we create 18 small ONs or 6 larger ONs (e.g. of 3 intermediate nodes), that will not change the impact on traffic as in all cases the same amount of terminals switches to ON. On the other hand, capacity and mobility level shall have an impact (sometimes significant) in the delay and power consumption measurements. As a result, the figures that follow provide specific evaluations for each of the aforementioned 27 testcases in order to have a clearer picture on the

impact of these attributes to the various performance metrics.

Table 3: Definition of testcases

Testcase	Number of nodes in the congested area switching to ON	Capacity (assumed in the links of the maximum flow problem)	Mobility level of each terminal (m/s)
1	6	1	0
2	12	1	0
3	18	1	0
4	6	2	0
5	12	2	0
6	18	2	0
7	6	3	0
8	12	3	0
9	18	3	0
10	6	1	1
11	12	1	1
12	18	1	1
13	6	2	1
14	12	2	1
15	18	2	1
16	6	3	1
17	12	3	1
18	18	3	1
19	6	1	2
20	12	1	2
21	18	1	2
22	6	2	2
23	12	2	2
24	18	2	2
25	6	3	2
26	12	3	2
27	18	3	2

Furthermore, Figure81 provides the average delay for delivering messages from all 40 terminals in the congested BS after the solution, for each one of the 27 investigated cases. This is also compared to the average delay in the congested BS, before the solution enforcement. As delay, is considered

the difference between the creation time of a message till the successful delivery of the full message to the final destination (which is always a BS). The horizontal axis shows the testcases and the vertical axis provides the average delay in seconds. In all cases, the proposed scheme seems to perform better compared to the congestion situation. The decrease in the delay is higher (around 35%) when 18 terminals switch to ON and decreases to around 25% and 15% when 12 and 6 switch to ON respectively.

Also, Figure82 illustrates the percentage of non-delivered messages from all 40 terminals in the congested BS after the solution, for each one of the 27 investigated cases. The horizontal axis shows the number of the testcases and the vertical axis provides the percentage of non-delivered messages. The general trend shows that as mobility level increases from 0 to 2 m/s, the percentage of non-delivered messages tends to increase due to more frequent break of connections.

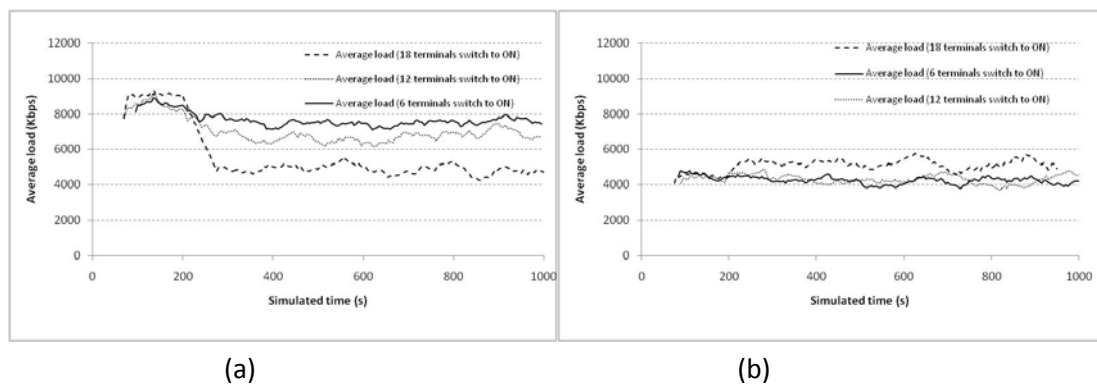


Figure80: Trend of load for all capacity and mobility levels of terminals (a) in the congested BS (BS1) before and after the solution enforcement and (b) in a neighboring, non-congested BS which acquired traffic after the creation of ON.

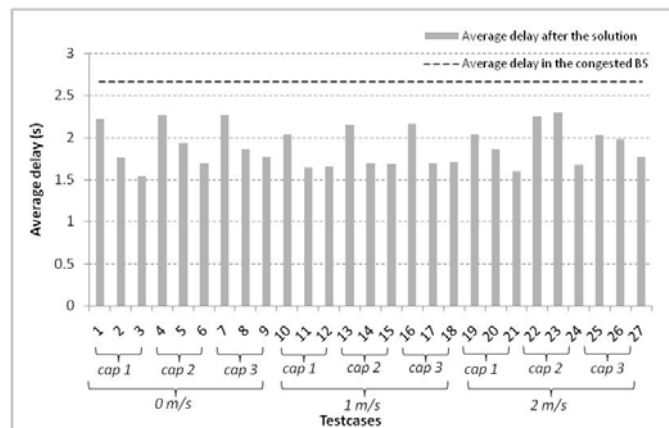


Figure81: Average delay measurements for the transmission of a whole message (64KB-1024KB) in each testcase.

Moreover, energy consumption has been estimated in each testcase for the congested BS, the terminals that switch to ON and the intermediate nodes. Figure83 illustrates the average gains in the transmission power of the congested BS. For the communication among the BS and the terminals the WINNER 5Bf propagation model has been used [20]. Also, for the communication among terminals the Friis formula has been utilized. The horizontal axis of Figure83 shows the simulated time in seconds while the vertical axis provides the average transmission power of the congested BS in Watts. The figure suggests that as more terminals of the congested BS switch to ON the energy savings in the BS range from 15 to 25%.

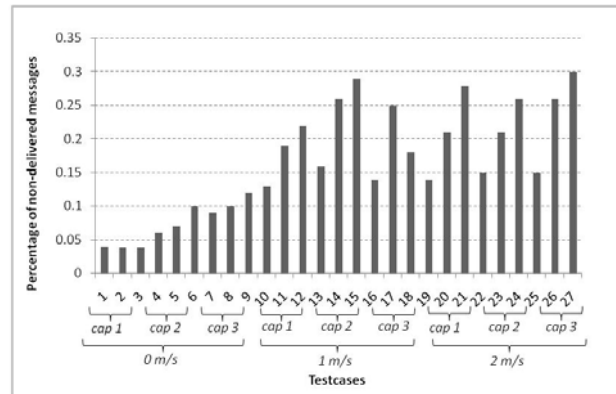


Figure82: Percentage of non-delivered messages in each testcase.

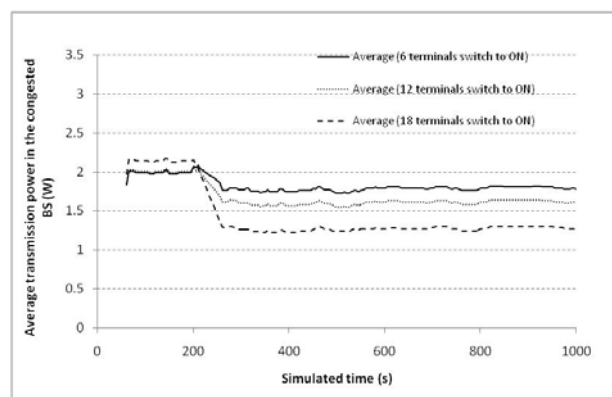


Figure83: Average transmission power (for all capacity and mobility levels of terminals) of the congested BS before and after the solution enforcement.

Figure84 provides also a graphical representation of the average transmission power of terminals that switch to ON in each testcase. The horizontal axis of the figure enumerates the testcases while the vertical axis provides the average transmission power of terminals that switch to ON. A decrease of the metric is observed which ranges from 10 to 50% depending on the testcase. Also, the decrease is greater in the cases where 6 terminals switch to ON, since these terminals tend to be nearer the edges of the cell, hence transmission power is greater before the solution. On the other hand, when 12 and 18 terminals switch to ON, there is a greater variety of distances of terminals from the centre of the cell, so the decrease in energy savings is lower.

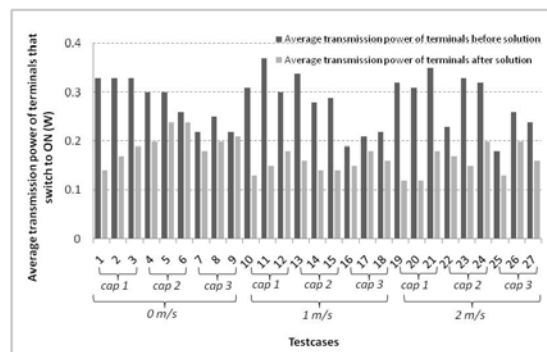


Figure84: Average transmission power of terminals that switch to ON in each testcase

Figure85 illustrates the average transmission power of intermediate nodes of the ON in each testcase. The horizontal axis of the figure shows the testcases while the vertical axis provides the average transmission power measured in Watts. In all testcases, an increase is observed which ranges from 8 to 50% depending on the testcase. When intermediate nodes are stationary higher increase is measured due to the fact that the always the same nodes acquire the extra traffic. As the average velocity of intermediate nodes increases, the transmission power tends to drop to lower levels compared to stationary nodes.

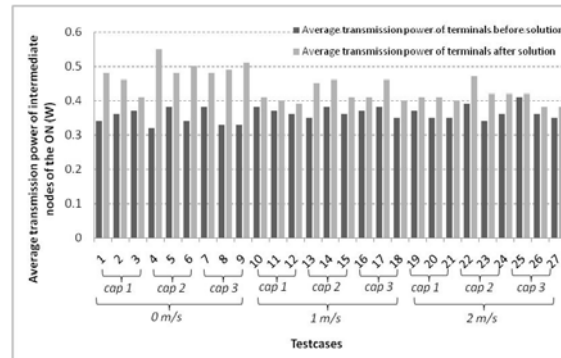


Figure85: Average transmission power of intermediate nodes of the ON in each testcase

3.8.3 Conclusions

According to the obtained results through the simulations that are provided earlier in this section, it is observed that terminals which act as intermediate nodes may experience an increase in their transmission power of 19% in average and it ranges from 8 to 50%, compared to the situation before the solution, depending on the testcase, e.g. whether they are stationary or moving, or depending on the allowed capacity. Specifically, in the most common case that an intermediate node can serve one terminal and its mean velocity is 1 m/s the increase in the transmission power is estimated to be 13%. At the same time, the terminals that switch from the congested BS to an ON may experience a decrease of their consumption of 27% in average and it ranges from 10 to 50% depending again on the testcase which is evaluated. More accurately in the most common case which was described before, the decrease of the transmission power is 43% in average. Through the creation of ONs in order to redirect traffic from the congested BS to neighboring cells, a reduction of 15-25% in the transmission power of the congested BS is observed. Also, the quality of communication is benefited, as delay of successfully delivered messages drops approximately 15-35%, compared to the congested situation, depending on the testcase. Furthermore, an average decrease of 15-40% has been achieved in the load of the congested BSs, depending on the number of terminals which switched to ON. Finally, extra traffic related to signaling for the establishment of ONs is limited due to the limited size of the ON which means that a small number of terminals need to exchange constantly control messages.

3.9 Route pattern selection in ad hoc network

3.9.1 Performance evaluation planning

3.9.1.1 Metrics to illustrate the performance of the algorithm

The main purpose of the algorithm is to select the most adapted pattern to select a route according to end user requested service and with the constraint to satisfy the Quality of Experience (QoE). The routing pattern selection algorithm is a qualitative algorithm. There is no meaning to perform a quantitative analysis. The reason, why quantitative results are not applicable, is that the algorithm

opportunistically adapts according to the end user service requested, and the metrics that are necessary to evaluate a quantitative result vary from an application family to another.

3.9.1.2 Benchmark references

The benchmark reference is not applicable.

3.9.1.3 Evaluation platform and model

The evaluation platform is based in the OMNeT++ simulator. The framework of simulation (see Figure 86) uses an emulation of the 802.11 protocol to manage the radio access. The propagation model is simply based on an attenuation of signal calculated from the distance between the node (pathloss is proportional to $1/\text{square}(\text{distance})$). An application layer allows generating transmission of data with different characteristics corresponding to the end user applications. The Routing pattern is implemented as a protocol, by analysing the header of IP frame to transmit it establish and select most adapted route to reach the destination.

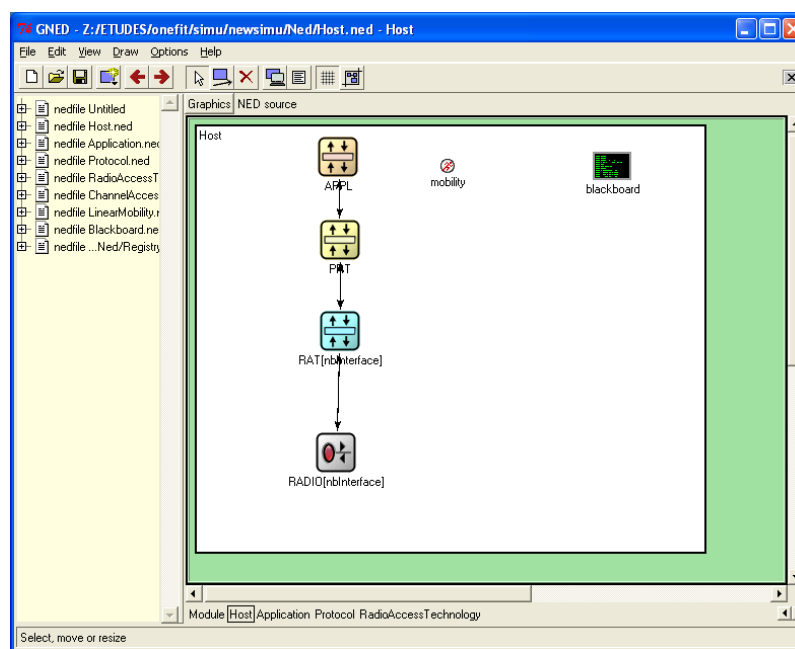


Figure 86: Framework of simulation

It is generated a topology with 20 nodes that are randomly distributed within the simulation area, in order to obtain a multi-hop topology (Figure 87).

Different types of transmissions (streaming, downloading, voice) are initiated from a source node to be transmitted to a pre-determined distant destination node (through multi-hop radio path). Depending on the requested service, the algorithm applies a set of patterns to determine the route.

Figure 88 depicts that the route to reach the destination is determined depending service requested by applying a different set of patterns for each family of application.

3.9.2 Performance evaluation results

As the main purpose of the algorithm is qualitative, to satisfy the end user QoE, changing the criterion of route' selection for each kind of service family, there are no metrics allowed to determine any objective performance.

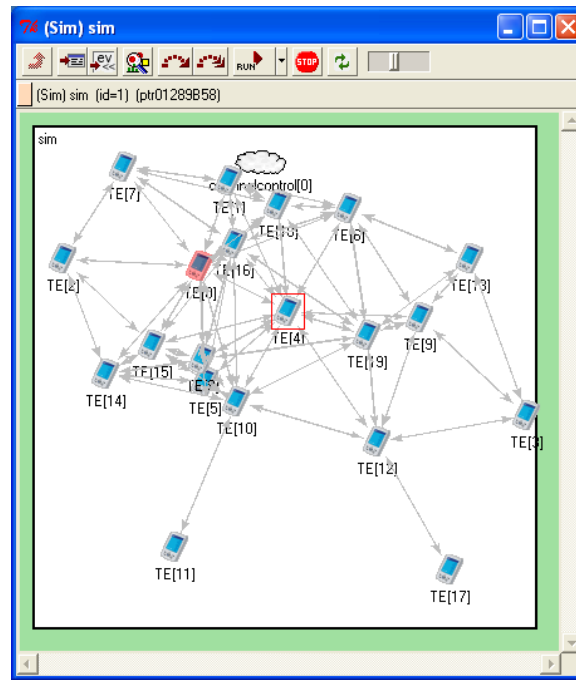


Figure 87: Evaluation topology

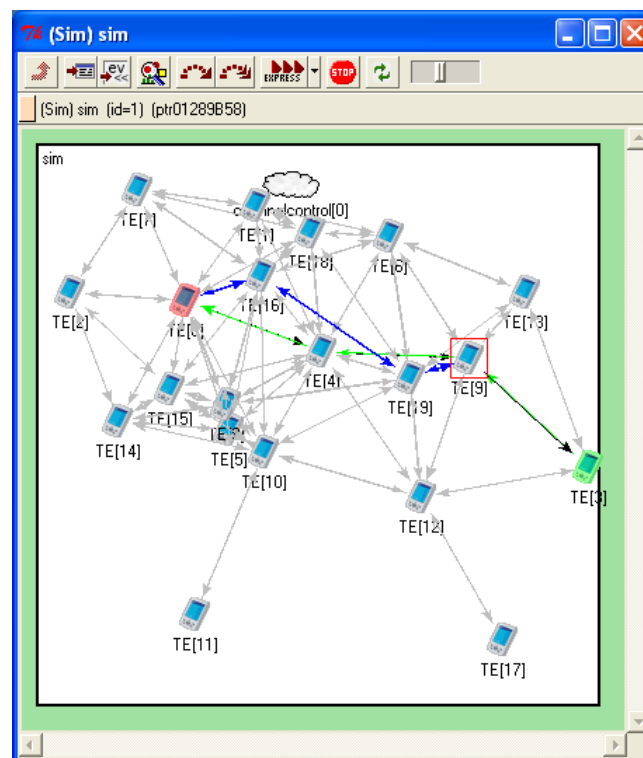


Figure 88: Example of route selection

3.9.3 Conclusions

By using the route pattern selection algorithm, we can achieve to satisfy the end user QoE. As qualitative result, we can deduce from the evaluation that in any topological and environmental conditions the algorithm allows to satisfy the end user QoE.

3.10 Multi-flow routes co-determination

3.10.1 Performance evaluation planning

3.10.1.1 Metrics to illustrate the performance of the algorithm

In the following paragraphs, results are presented related to the performance of the proposed algorithm in terms of:

- percentage of topologies the optimization is applicable
- global throughput gain in the traffic flows

3.10.1.2 Benchmark references

For benchmarking, the situation before the solution enforcement is considered, which means independent route flows with no optimization with use of network coding with multi flows management).

3.10.1.3 Evaluation platform and model

The evaluation platforms are twofold.

a) Proof of concept on an OMNET evaluation platform model

In a first stage, an OMNET simulation platform on a modified DYMO routing protocol implemented on the Wifi inetd OMNET implementation.

1. A flow is usually identified by the tuple (source IP address, destination IP address, source port number, destination port number). For sake of simplicity, in the simulator the flow is identified by the uint32_t value of the IP source address. It follows that only one flow can be established by the same source node.
2. Even if multicast is supported at the application layer, no multicast ad-hoc routing algorithm is implemented in the actual version of the simulator. As an example, assuming to use reactive ad-hoc routing protocols, to find a single route for the first flow from Node 0 to Node 2 and Node 5, a routing algorithm like the Multicast-DYMO algorithm would be required. Since this is not available, two unicast communications have to be established toward the two destinations of the same flow: a first one between Node 0 and Node 2 and a second one between Node 0 and Node5.
3. The Network Coding solution can be simulated using Constant Bit Rate (CBR) traffic only and not with video streaming. Indeed, the Network Coding solution assumes that discovery messages are flooded at the flow initialisation from the source to the destination in order to discover the network topology. However, when considering video streaming, the client requests the video to the server via the RTSP handshake: it follows that the topology discovery is triggered by the client and not by the server. This has a non negligible impact of the NC table construction.
4. In order to avoid this problem, the simulation chain has been modified to trigger the CBR traffic generation directly at the server (i.e., without client request).
5. Each module of the communication chain is described in the source file with the same name (e.g., the CMON module is characterized in the CMON.cc file)
6. The network coding can be disabled setting the parameter NC=0 in the omnetpp.ini:
7. `sim.*.net_L.routing.network_coding = 1 ;network coding`

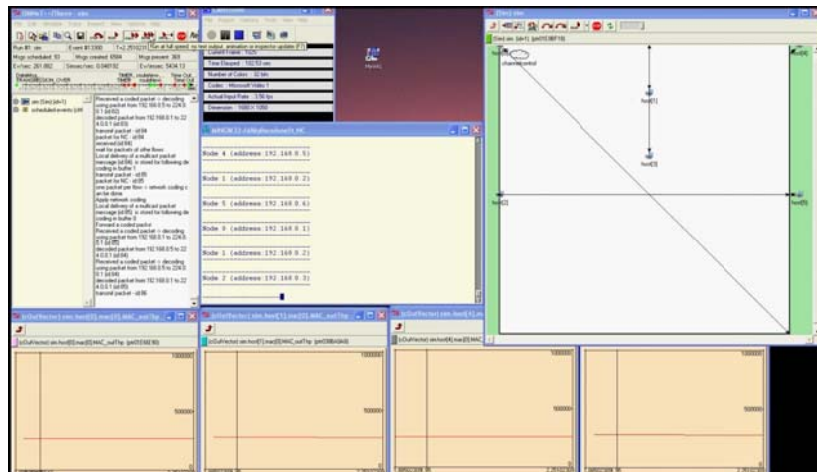


Figure 89: Algorithm execution on the butterfly topology

b) C++ simulation evaluation platform model for performance analysis on randomized samples of topologies and flows

In a second stage, the algorithm has been implemented as a pure C++ simulation algorithm.

3.10.2 Performance evaluation results

As stated in section 3.10.1.3, we implemented the network coding algorithm as a C++ program with input files defining the topology and two flows (being either 1to1 -which means a traffic from 1 ingress node to 1 egress nodes- or 1to2 -which means a traffic from 1 ingress node to 2 egress nodes-). The application computes the network coding application capabilities, corresponding paths and the theoretical percentage of gain in terms of throughput by number of packets exchanges between pair nodes.

3.10.2.1 Results on arbitrary defined topologies

We first applied the algorithm on arbitrary defined topologies, some of them presented in Figure90. As shown in Table 4 and Table 5, the application on these specific topologies and flows give good results, with particularly good improvements with the use of the delegated nodes optimization.

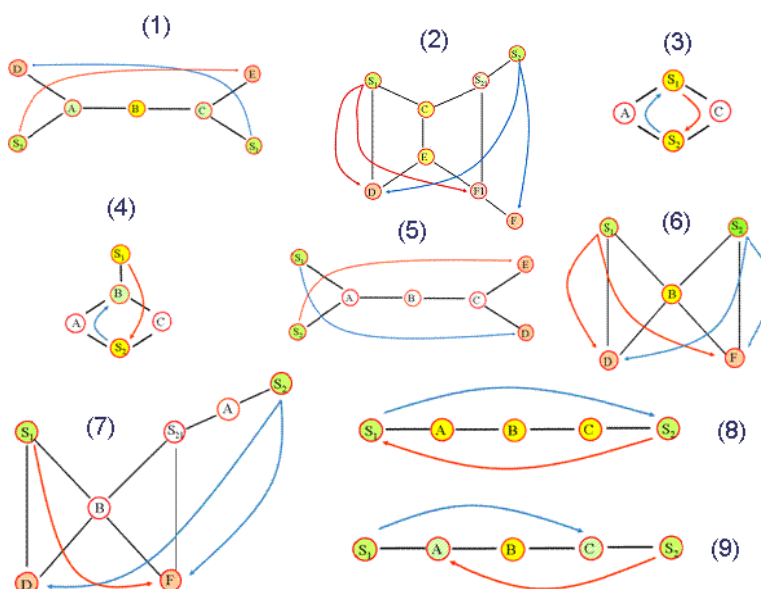


Figure90:Different topologies and flows

Column (1) in Table 4 indicates capability to use the network coding algorithm without delegated nodes optimization, column (2) indicates the capability to use the algorithm with the network coding optimization. The term EXT indicates that an extended version of the definition of the delegated node could process the optimization. Table 5 gives the percentage of topologies these optimizations are applicable, and the global percentage of throughput gain.

Table 4: Optimization results.

Topology and flows	Table Column Head		
	(1)	(2)	Throughput gain (%)
(1)	NO	YES	12.5
(2)	NO	YES	25
(3)	YES	-	25
(4)	NO	YES	20
(5)	NO	NO	0
(6)	YES	-	25
(7)	NO	EXT	16.6
(8)	YES	-	37.7
(9)	NO	YES	16.6

Table 5: Optimization results.

(1) to (9)	(1)	(2)
Algorithm applicable	33%	78%
Global gain	9.7%	14.7%

3.10.2.2 Results on randomized topologies and flows

In a second step of the optimizations validation, we applied the optimizations on series of 200 samples of randomized topologies of 6 to 10 nodes, on a 4x4 grid, with the capability for the (x,y) located node to communicate to the $x\pm 1$ and/or $y\pm 1$ located nodes.

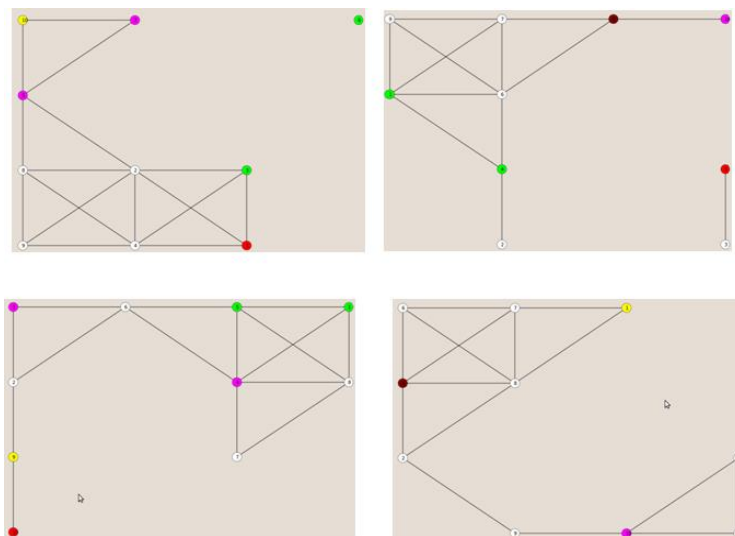


Figure 91: Samples of generated topologies

For each of these sets of samples, 2 samples of traffic flows between nodes have been randomized, with a distance of at least 2 hops. These 2 traffic flows are both with one or two destination nodes.

Figure92 gives for the three kind of flows (two traffics 1to2, two traffics 1to1 and one traffic 1to2 and one traffic 1to1), on the randomized samples the traffics can be set (without optimizations), the percentage an optimization is applicable. In abscissa is indicated the number of nodes, and in ordinate the percentage of optimization applicability. We may see that this percentage decreases with the density of the network. The explanation is that there are fewer situations of flow paths crossing in a randomized draw of the samples.

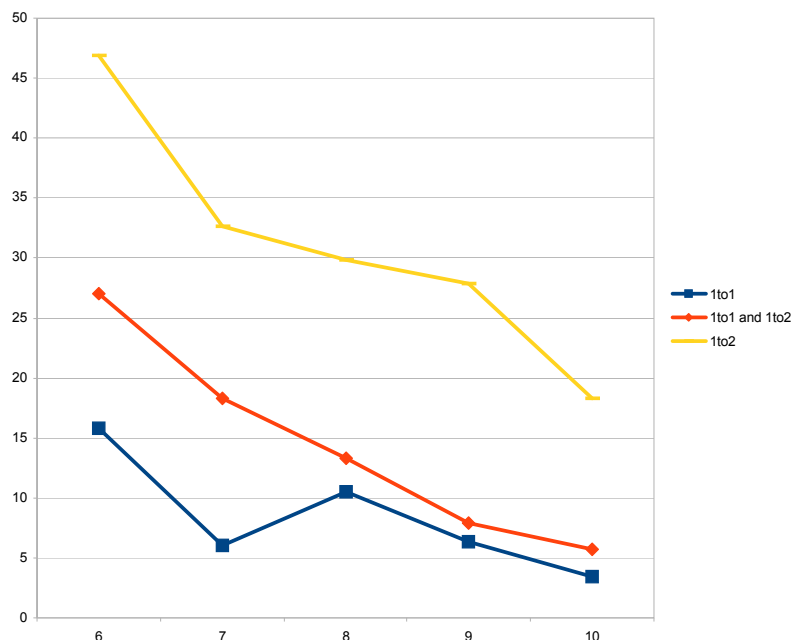


Figure92: Percentage of optimization applicability as a function of the number of nodes

Figure93 presents the global gain of the network coding optimizations for all the situations where the traffic is possible (with or without optimization). In abscissa is indicated the number of nodes, and in ordinate is indicated the global percentage of gains with the use of network coding optimization with delegated nodes on the global samples the traffics were effective. For example, for the samples of randomized distributions of 6 nodes with two 1to2 traffics, network coding optimization is applicable in 46,9 %, with a final gain of 8.66% of gain, which means a global gain of 18.4% in the samples the optimization is applicable (quite similar to the figures in the case of specific topologies).

Figure94 presents the gain of the delegated node optimization with respect to the initial network coding optimization algorithm proposed in section 0. We may see a real increase in the gains with the use of this optimization, in particular in the situation of two 1to2 flows.

Although the definition of a delegated node seems to be restrictive, as the initial and terminal nodes need to have a unique neighbour, in the randomized selection of nodes we may state a real increase of the topology candidates for flows optimization. After a post analysis of the results, it appears that most of the time the optimization on bi-directional flows is the most applied, also with 2 1to2 flows situations.

3.10.3 Conclusions

We did present a first proposal of network coding optimization on multi-flow route co-determination, reminded from further studies results [46]. Optimization on this initial algorithm follows to extend the set of topologies on which the multi-flow route co-determination is applicable, with the introduction of delegated nodes. Results on an implementation of these optimizations are given, in a first time on a specific set of topologies and flows, and in a second time on randomized samples of topologies and flows. The results obtained are very promising, as they show good

improvements on the throughputs in terms of number of data packets to be exchanged between pair nodes. The integration of the delegated nodes really improves the throughput gains. But nevertheless, the delegated node definition is really restrictive. Future work could lead to the definition of such protocol to evaluate the gains of a more general definition of these delegated nodes. The evaluation of the gains not on randomized topologies and flows, but on general missions real ground topologies is also a potential future work, along with the evaluation of the impact of mobility, variable stability links and self-healing procedures.

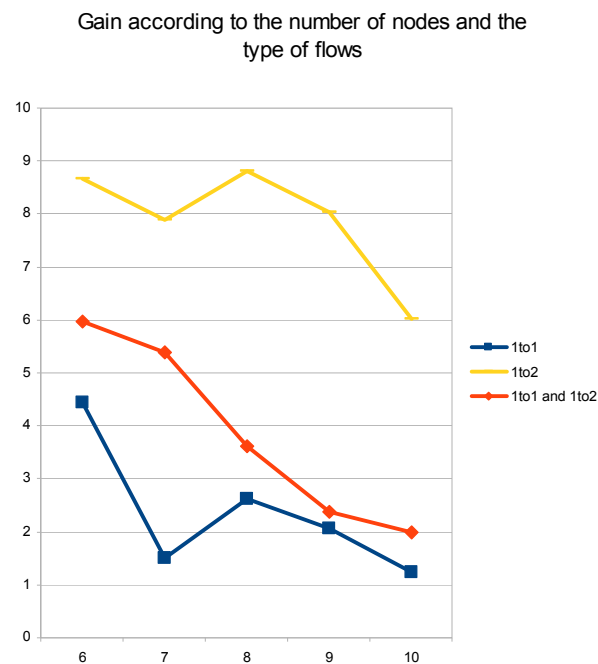


Figure93: Global percentage of gain with the use of NC optimization

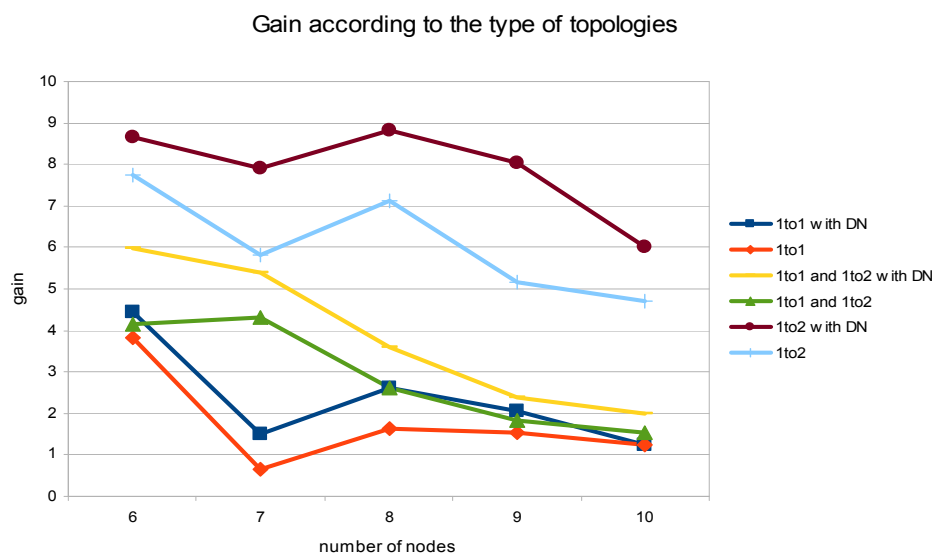


Figure94: Comparison between optimization with/without delegated nodes

3.11 QoS and Spectrum – aware Routing Techniques

Modeling and implementation is still ongoing. Performance evaluation results will be reported as part of D4.3 deliverable.

3.11.1 Performance evaluation planning

3.11.1.1 Metrics to illustrate the performance of the algorithm

The main performance evaluation will be based on the following:

- Delivery Ratio: The ratio of the number of packets successfully delivered to the total number of packets sent.
- Latency: The time difference between the time that a packet is created and is delivered to the destination.
- Path Length Optimality: The difference between the path created based on our algorithm and the best possible path at that instance.
- Control Overhead: The amount of routing control packets generated by the protocol.

3.11.1.2 Benchmark references

The benchmark references include AODV, DSDV, DYMO and OLSR protocols.

3.11.1.3 Evaluation platform and model

OMNeT++ simulator is used as the simulation platform. The simulations will be based on a number of mobile units that are randomly distributed within the simulation area. All of nodes implement the proposed algorithm for routing the data traffic in the network. A number of random transmissions will take place and the routing protocol will create and maintain routes at all time. The following represent some of the main simulation assumptions:

- Link layer protocol used: IEEE 802.11
- Routing protocols for comparisons: OLSR, DSDV and AODV
- Mobility models: Chiang, Gauss Markov and Tracl mobility models
- Propagation models: Pathloss + Log-normal shadowing and Rayleigh fading

3.11.2 Performance evaluation results

Modeling and implementation is still ongoing. Results will be provided as part of D4.3 deliverable.

3.11.2.1 Planning of future performance evaluation activities

- Integration of spectrum awareness module with the base implementation of OLSR is expected by Q3-2012.
- The first set of results which are based on performance comparison of the OLSR and other most popular routing protocols is expected by Q3-2012.
- The second set of results, following implementation and evaluation of proposed modification to OLSR algorithm, is expected in Q4-2012.
- All results will be reported in D4.3 deliverable.

3.11.3 Conclusions

Results analysis and conclusions will be provided as part of D4.3 deliverable.

3.12 Techniques for Network Reconfiguration – topology Design

3.12.1 Performance evaluation planning

3.12.1.1 Metrics to illustrate the performance of the algorithm

The metrics considered to measure the effectiveness of the algorithm are as follow:

- min TX Power per node (to remain k-connected)
- Average and Maximum node degree,
- Average and Maximum transmission radius
- Total throughput.
- Average power consumption.
- Control/signalling overheads.

Above metrics are analysed against, varying K connectivity, network size, node density and mobility.

3.12.1.2 Benchmark references

Two sets of benchmark references have been identified and are considered for performance comparisons:

- The performance bound is provided by the centralized approach/analysis through Mixed Integer Linear Programming (MILP) under system constraints. The optimal solutions are obtained under the conditions of global knowledge and centralization.
- The state of the art localized and distributed topology control algorithms/protocols (CBTC, LMST, K-Neigh).

3.12.1.3 Evaluation platform and model

3.12.2 Performance evaluation results

PHASE i

The mathematical analysis is done for the phase one using IBM ILOG CPLEX. Here, optimal minimum power per node is determined under path loss and flow constraints with symmetric topology (to enable RTS/CTS procedure of 802.11 MAC). For **20 nodes**, the following are the optimal power values per node for different values of K (Representing the reliability) are obtained:

Table 6:Analytical results (20 nodes) for CP,DP and IP modes

K - values	1 st Formulation Optimal min. Power [Continuous Power mode]	K- values	2 nd Formulation Optimal min. Power [Discrete Power mode]	K- values	3 rd Formulation Optimal min. Power [Incremental Power mode]
2	0.98	2	2.6	2	2.08
3	2.10	4	3.9	4	3.15
4	3.15	6	7.2	6	6.70
5	3.97	8	8.7	8	7.60
6	4.89	10	10.5	10	9.80
7	4.99	12	12.60	12	12.01
8	5.60				

The results as depicted in Table 6above indicate:

- Continuous power model provides least power values however it considers infinite power levels to be available at all network nodes.
- The incremental power model provides minimum power levels as compared to discrete model while taking into account a finite set of available power levels in heterogeneous network (different maximum power levels per node).

In the next set of results as shown in Table 7, (k set as 2 (bidirectional topology) and number of nodes set to 5, 10 and 15), the optimal levels of power given by DP and IP models are given. In the 2nd formulation set (DP), as the network nodes increase there is almost 70 to 80 % increase in optimal power, however 3rd formulation (IP) not only provides less power levels than DP it also shows less increase in respective power levels.

Table 7: Analytical results for $k = 2$ (and variable number of nodes) for DP and IP modes

Number of nodes	2 nd Formulation Optimal min. Power [Discrete Power mode]	Number of nodes	3 rd Formulation Optimal min. Power [Incremental Power mode]
5	1.25	5	0.20
10	2.05	10	0.85
15	2.7	15	2.0834

PHASE ii/iii:

Modeling and implementation is still ongoing. Results will be provided as part of D4.3 deliverable.

3.12.2.1 Planning of future performance evaluation activities

- Integration of interference constraint into current model is expected by mid-Q3-2012.
- The Development/implementation of distributed version is expected by end-Q3-2012.
- The second set of results, through Implementation and testing of algorithm on the system simulation platform is expected in Q4-2012 and will be reported in D4.3 deliverable.

3.12.3 Conclusions

Initial results indicate that the DP and IP models can provide practical yet optimal power levels to minimize the power utilization while maintaining K connectivity. Future further steps include addition of the interference based on SINR in the above sets of formulation and implementation of a distributed variant.

3.13 Application cognitive multi-path routing in wireless mesh networks

3.13.1 Performance evaluation planning

3.13.1.1 Metrics to illustrate the performance of the algorithm

Metrics selected for validating algorithm's performance:

- Achieved aggregated bandwidth – total bandwidth which can be provided on access side of the struggling WMN AP (limited by access radio technology – 802.11g) by establishing multiple paths in WMN backhaul.

- Stability of the selected paths – multiple paths which are established in the backhaul of the WMN can result in increased interference and packet reordering problems. Also mobility of end users will result in changes in backhaul traffic patterns which may require multiple path recalculations.
- Impact of multi path packet routing on QoS provided to end users.
- Signalling overhead – trade-off between the amount of gathered contextual data and performance of the algorithm will be examined (provided in D3.3).

3.13.1.2 Benchmark references

Benchmark references which will be used for evaluation of the algorithm:

- OLSR single path routing protocol as standard solution for routing in modern WMNs. Plan is to evaluate performance of the proposed algorithm against performance (achievable load balancing and WMN bandwidth capacity) of the underlying OLSR protocol.
- The same algorithm but without awareness about profile of the access traffic. This comparison will be used to show the problems which can arise when algorithm is not aware of the QoS requirements for different applications and services.

3.13.1.3 Evaluation platform and model

Demonstration will address OneFIT's scenario 5 "Opportunistic resource aggregation in the backhaul network". The addressed use case is "Opportunistic backhaul bandwidth aggregation in unlicensed spectrum". Demonstration platform includes (see Figure 95):

- Wireless mesh network (WMN) test-bed with open platform access points (APs) based on MikroTik router-boards and OpenWRT system.
- Database of contextual information.
- Traffic generator for emulating traffic flows.
- Simple network management protocol (SNMP) for network monitoring and contextual data gathering.
- Optimized link state routing (OLSR) protocol for route discovery, establishment and maintenance.
- End user's terminals.

The main idea behind this demonstration is to show how multi-path routing can provide aggregation of available backhaul bandwidth resources in WMNs and provide better QoS level for the end users. The benchmark for evaluating achieved backhaul bandwidth aggregation is the single path OLSR protocol.

This demonstrator is a real test-bed and therefore the algorithm is evaluated in a real radio environment. Interferences are coming from the surrounding WiFi networks and also interferences are generated in the test-bed in order to monitor impact of improper channel selection and distribution on packet loss rate in WMN. Different 802.11g channel distributions among access interfaces of nodes of the test-bed are tested. Also, different spatial channel distributions are tested for backhaul interfaces (based on the 802.11a standard) of test-bed nodes. High impact of internal interference (result of poor channel distributions) on number of lost packets is identified. Impact of topology changes and transmission power levels on interference within the WMN test-bed are also inspected.

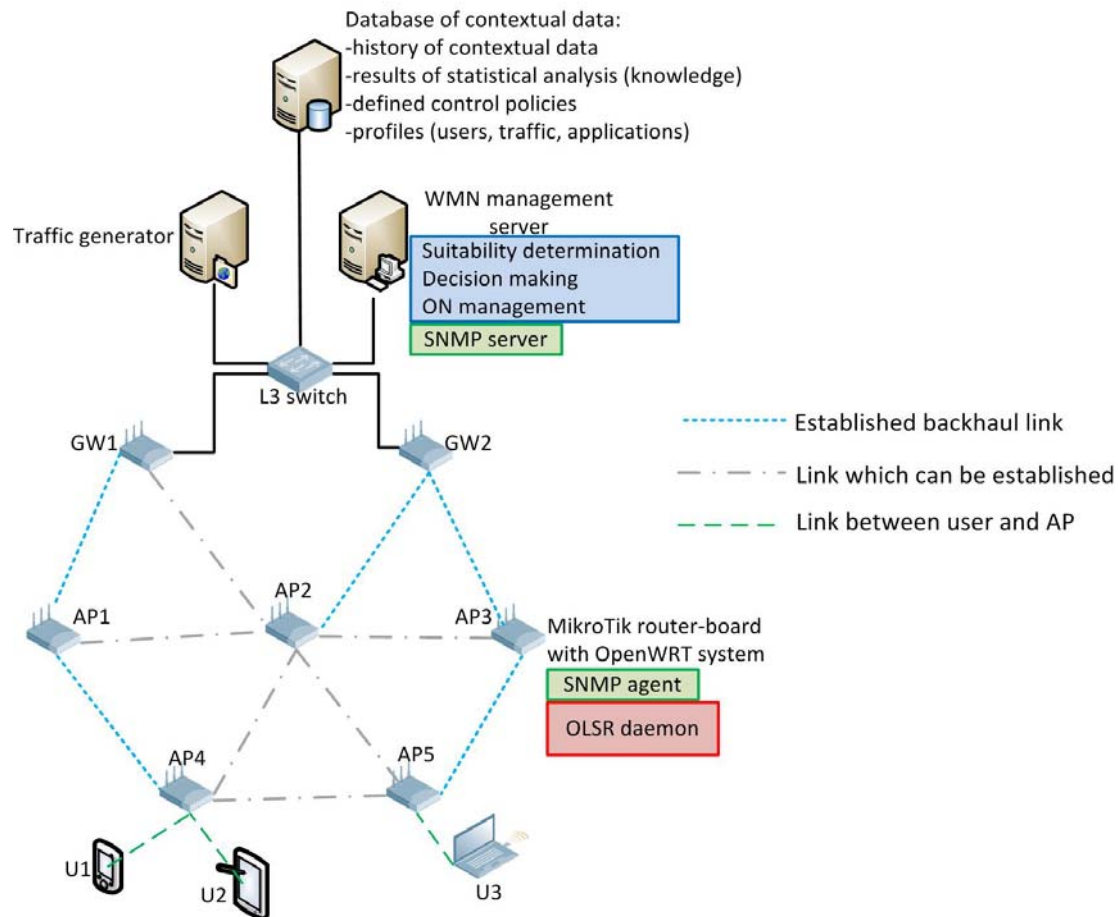


Figure 95: Evaluation platform for backhaul bandwidth aggregation in WMNs

The test-bed shown in Figure 95 represents a well constructed standard WMN. This is due to the facts that:

- WMN nodes have three radio interfaces (one for access and two for backhaul communication);
- Access is provided over the 802.11b/g standard;
- Backhaul communication is provided over the 802.11a standard;
- Topology allows every WMN node to “see” at least two other WMN nodes;
- Topology allows at least one path from every WMN node to all of available WMN GWs;
- Standard OLSR routing protocol used (developed for WMNs);
- Monitoring is done over SNMP protocol which is supported by all commercial devices.

Various static (links manually created) and dynamic (links created by the underlying MAC and routing protocols) topologies of the open platform WMN test-bed are investigated. Topology depicted in Figure 95 is selected as the one which provides the most possibilities for multiple paths selection, which allows the implemented algorithm to find solutions among sets of available solution thus demonstrating the decision making ability of the algorithm. The algorithm will be tested in larger network deployments in order to provide validation of its scalability.

3.13.2 Performance evaluation results

Implementation of the algorithm is not dependent on WMN size, topology, number of interface of WMN nodes and used RATs. It was developed to be generic. After development it is successfully validated on the WMN test-bed shown in Figure 95. Results of this validation are presented bellow.

The proof of concept experiments are conducted in order to assess ability of the proposed algorithm to find appropriate multiple path solution and enable the backhaul bandwidth aggregation for a struggling APs. Experiments are validated on WMN test-bed shown in Figure 95. Traffic generator is sending UDP packet streams to nodes of the experimental network in order to simulate different backhaul traffic patterns.

All of the nodes in the WMN test-bed have three radio interfaces. Two of them are utilizing 802.11a protocol for backhaul communication and one is used for providing 802.11g connection for the end users. OLSR protocol with ETX metric (expected transmission count) is used as the underlying single path routing protocol. All of the wireless links in the WMN can support maximum of 30Mbit/s of user data traffic (in accordance to 802.11a and g standards). The threshold for the number of hops for candidate paths is set to 3. We demonstrate backhaul bandwidth aggregation relative to AP4 and AP5 (see Figure 95). AP1, AP2, AP3, U1, U2 and U3 will be configured as sinks for the UDP streams. In the access side of the AP4 we consider the *type 4* access traffic. Access traffic for AP5 can be considered as *type 2* or *type 3*. We will present 4 experiments for the WMN topology presented in Figure 95. Setups of the proof of concept experiments and their results are presented in Table 8.

For example, in the first experiment AP1, AP2 and AP3 are set as sinks for UDP traffic streams. The bandwidth which is reserved by these sinks is presented in Table 8 in Mbit/s. Let's assume that users connected to AP4 require total of 10Mbit/s of UDP traffic and user at AP5 requires 15Mbit/s. Users connected to AP4 can be provided with the necessary bandwidth over the existing path AP4-AP1-GW1. However, user connected to AP5 cannot be provided with the required bandwidth, because no single path can be established with the sufficient capacity (in the light of the current bandwidth usage in the WMN). Therefore, the multiple path solution is derived by using the algorithm described in this paper. Algorithm provides the solution (see Table 8) in the form of the path, which when joined with the current path AP5-AP3-GW2, with bottleneck link AP3-GW2 (marked red in the Table 8) which has 5Mbit/s available bandwidth capacity, provides aggregated backhaul bandwidth, which is enough to meet the current demand at the access side of the AP5. The additional path is AP5-AP2-GW2 (marked green in Table 8) and it provides 10Mbit/s (given in parentheses next to the path in Table 8). Solutions for all other experiments are given in Table 8 as well.

Table 8: Setup and results of the proof of concept experiments for backhaul bandwidth aggregation algorithm

Exp #	AP1 sink	AP2 sink	AP3 sink	AP4 req	AP5 req	AP4 bottle	AP4 solution	AP5 bottle	AP5 solution
1	15	20	25	10	15	OK	OK	AP3-GW2 (5)	AP5-AP2-GW2 (10)
2	28	20	15	11	10	AP1-GW1 (2)	AP4-AP2-GW2 (9)	OK	OK
3	15	25	15	5	25	OK	OK	AP3-GW2 (15)	AP5-AP4-AP1-GW1 (10)
4	20	25	10	20	10	AP1-GW1 (10)	AP4-AP5-AP3-GW2 (10)	OK	OK

In the experiment 1, AP4 does not experience shortage of the backhaul bandwidth, which is depicted by OK in the column defining the bottleneck link of the AP4's current path and solution column for the AP4 (multi-path routing for AP4 is not required).

The algorithm runs on a well dimensioned centralized server which has access to contextual database with latest values of contextual parameters. Algorithm runs on a server which performs management of the whole network and one of management tasks is multipath routing control. Custom WMN monitoring system gathers a bulk of contextual parameters every one minute, therefore the algorithm will react to changes in contextual parameters in no later than one minute

and a small time interval needed for decision making regarding multiple paths set selection (for the simple WMN test-bed, as shown in Figure 95, algorithm took average of 0.3 seconds). Regarding the power consumption of the multipath routing solution, it requires that dormant wireless interfaces of WMN nodes are turned on. This increases system power consumption. However, the algorithm proposes opportunistic multipath routing when single path routing cannot deal with the increased congestion and poor load balancing in the backhaul segments of WMN. Increased congestion results in more retransmissions as well as decreased bandwidth provided to end users. Less bandwidth provided to end users and more retransmission of packets means that they will spend more time communication with infrastructure nodes which directly decreases the battery level of mobile users. Therefore, increased power consumption in the infrastructure side as a result of utilization of additional network interfaces is compensated by decreased number of packet retransmissions and increased bandwidth provided to end users which allows them to finish their data transmission more quickly allowing them to turn off their wireless interfaces and thus save battery.

The main concern when using multipath routing in WMNs is its impact on QoS provided to end users. The multipath routing provides more bandwidth to the end users, but tends to increase interference in the backhaul paths, which results in more retransmitted packets, and result in packet reordering problems and increased jitter levels. The algorithm distributes users' traffic across multiple paths in a manner which doesn't result in packet reordering problems (one user/one independent application over one backhaul path – there is no dividing one traffic flow over multiple backhaul paths). This results in slightly decreased level of resource utilization, but increased level of QoS provided to end users.

The results of impact of multipath routing on QoS provided to the end users will be shown and discussed for a test-bed setup as shown in Figure 96. Different combinations of end user locations are tested and all of them yielded similar results, therefore, for the sake of clarity of presentation, a discussion of results related to setup presented in Figure 96 is provided.

There are two users. U1 is connected to WMN AP4, which is considered a candidate for multipath routing (together with AP5 – topology limitation). U2 is connected to AP1. There are two main test cases:

- U1 receives all the traffic over the path GW1-AP1-AP4;
- U1 receives traffic over the new path GW2-AP1-AP4.

Backhaul traffic patterns are established by sending traffic flows of selected bit rate to WMN nodes (simulating users' requests at other WMN nodes). These bit rates are gradually increased in order to simulate different levels of congestions among backhaul paths. Backhaul channels are carefully selected in order to minimize interference in a test bed which is located in a relatively small laboratory. Access interfaces of all WMN nodes, apart from AP1 and AP4 are turned off. However, interference in 2.4GHz band from environment are significant (23 different access networks are identified). Four types of applications are requested by U1 and U2:

- VoIP – bandwidth requirement 0.2Mbit/s;
- Video 1 – video stream of low quality with 1Mbit/s bandwidth requirement;
- Video 2 – video stream of medium quality with 1.5Mbit/s bandwidth requirement;
- Video 3 – video stream of high quality with 2.5Mbit/s bandwidth requirement.

Based on these requests a UDP traffic generator generates a constant bit rate stream of a certain rate to end users. IPERF QoS monitoring tool is installed on U1 and U2. Jitter levels, number of lost UDP packets and achieved throughput are monitored as QoS indicators. One test case consider one combination of requested applications (i.e. U1 requests Video 1 and U2 requests Video 3), one background backhaul traffic pattern and whether or not U1 receives its traffic over path GW1-AP1-

AP4 or the new path GW2-AP1-AP4. There are 7 different backhaul traffic patterns and two combinations of requested applications (U1 requests Video 3 and U2 requests Video 1, U1 requests Video 2 and U2 requests VoIP). Every test case runs for an hour. After an hour average values for achieved throughput, percentage of lost packets and jitter level on every user is gathered. Total simulation time for presented results is 28 hours.

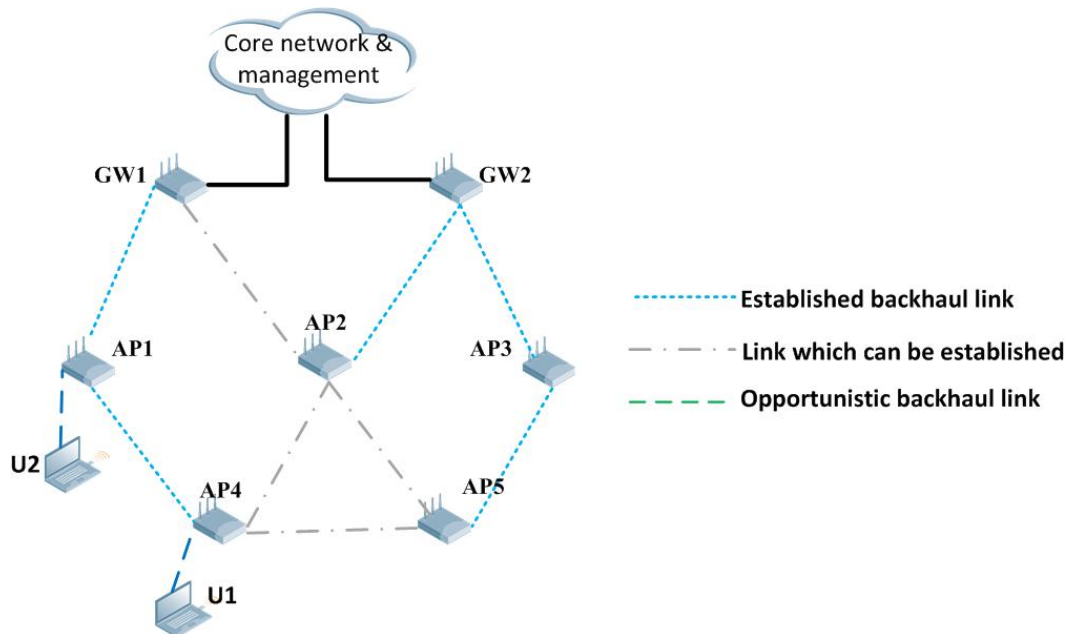


Figure 96: Test-bed setup for estimation of impact of multipath routing on QoS provided to end users

Backhaul traffic patterns used in experiments are showed in Table 9. UDP traffic generator is used for sending traffic of a selected bit rate towards nodes AP1, AP2 and AP4. For example, in case 6 8Mbit/s is sent to every of these nodes. This means that link GW1-AP1 transfers 16Mbit/s in total which makes it a bottleneck link and as a solution a path GW2-AP2-AP1 is created in order to offload a part of traffic from GW1 to GW2. UDP generator is used in order to avoid problems of packet retransmissions of TCP protocol.

The first case analyzed is when U1 requests Video 3 type of application and U2 requests Video 1 type of application. Average throughput provided to U1 and U2 for the case of backhaul bandwidth aggregation through multipath routing and in case when there is no backhaul bandwidth aggregation (single path routing) is shown in Figure 97. The results show that both U2 and U1 benefit from multipath routing (bandwidth aggregation) in a sense that average throughput increases for both users. Average throughput for U1 increases because he is rerouted to a less congested path GW2-AP2-AP4. Throughput of U2 increases because path GW1-AP1-AP4 is offloaded since U1 is rerouted over the new path towards GW2. The same logic stands for UDP packet loss percentage for U1 and U2 as shown in Figure 98. As the backhaul traffic pattern changes towards more congested situation, the packet loss percentage rises drastically. However packet loss percentage is less in case of multipath routing (bandwidth aggregation). Also, according to obtained results, relevant QoS parameters tend to show more stability in their values when multipath routing (aggregation) is established.

Table 9: Experimental setup

Test case number (UDP traffic sent to WMN nodes)						
1	2	3	4	5	6	7

WMN node	AP1	4Mbit/s	5Mbit/s	5.5Mbit/s	6.5Mbit/s	7Mbit/s	8Mbit/s	9Mbit/s
	AP2	4Mbit/s	5Mbit/s	5.5Mbit/s	6.5Mbit/s	7Mbit/s	8Mbit/s	9Mbit/s
	AP4	4Mbit/s	5Mbit/s	5.5Mbit/s	6.5Mbit/s	7Mbit/s	8Mbit/s	9Mbit/s

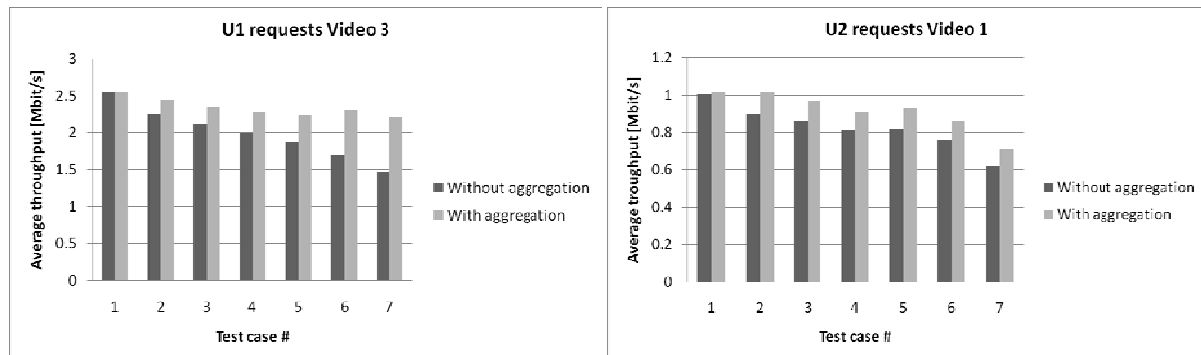


Figure 97: Average throughput achieved by U1 and U2 in case of single path routing and in case of multipath routing

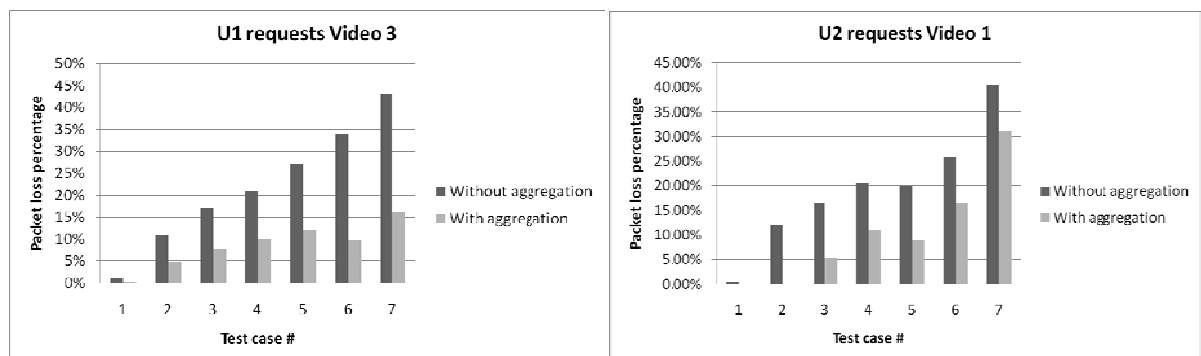


Figure 98: Packet loss percentage suffered by U1 and U2 in case of bandwidth aggregation and without it

Legacy multipath routing approaches in WMNs resulted in significant jitter related problems. The proposed multipath routing algorithm avoided problems of packet reordering by providing application (access traffic) profile awareness. Results in Figure 99 show that multipath routing tends to achieve lower jitter level and more stable jitter value in contrast with legacy (application unaware) multipath routing.

The second analyzed case is when U1 requests Video 2 and U2 requests VoIP type of application. Figure 100 shows how the average throughput received by both users is affected in case of multipath routing (backhaul bandwidth aggregation) and single path routing. These results are in line with results of the first test case. Also, packet loss percentage results shown in Figure 101 are in line with throughput related results. Results shown in Figure 102 confirm that the proposed application cognitive multipath routing achieves better jitter results when compared with underlying single path routing.

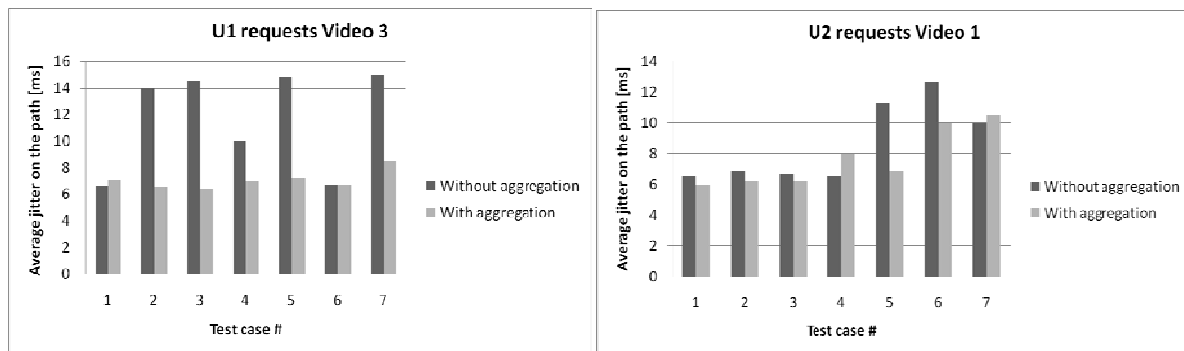


Figure 99: Average jitter on a path for U1 and U2 in case with and without backhaul bandwidth aggregation

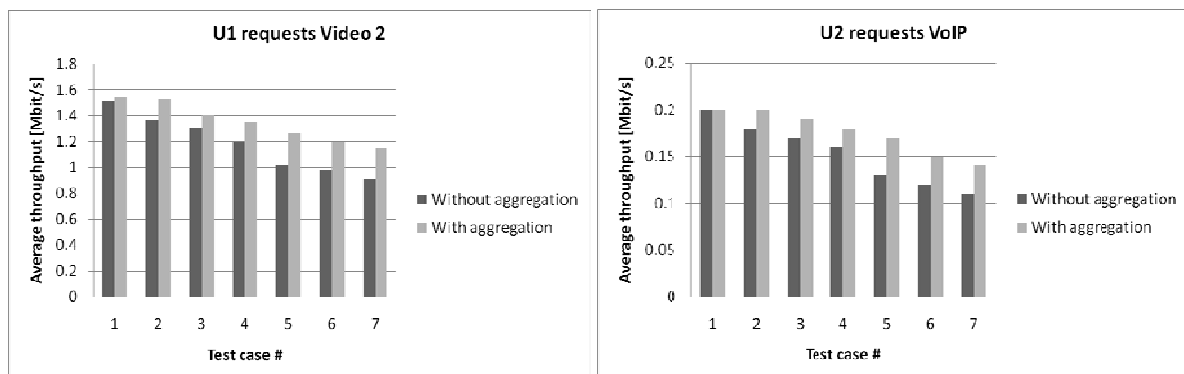


Figure 100: Average throughput achieved by U1 and U2 in case of single path routing and in case of multipath routing

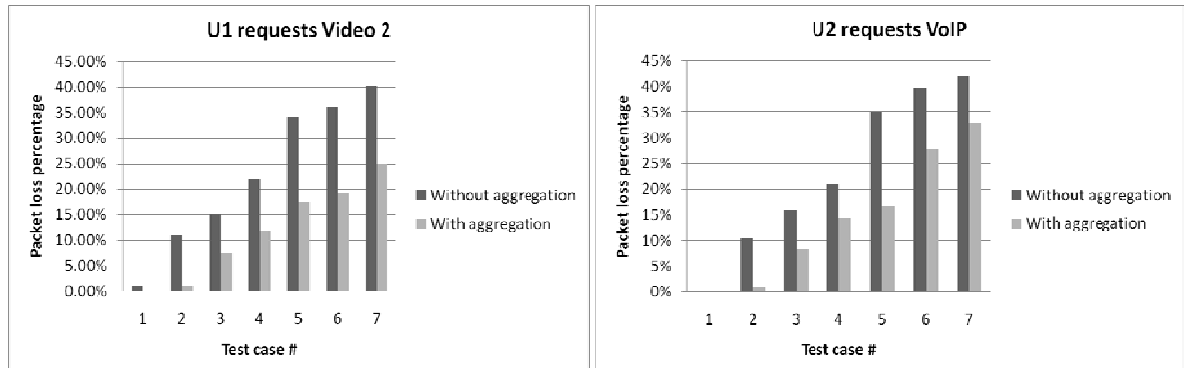


Figure 101: Packet loss percentage suffered by U1 and U2 in case of bandwidth aggregation provided by multipath routing and without it

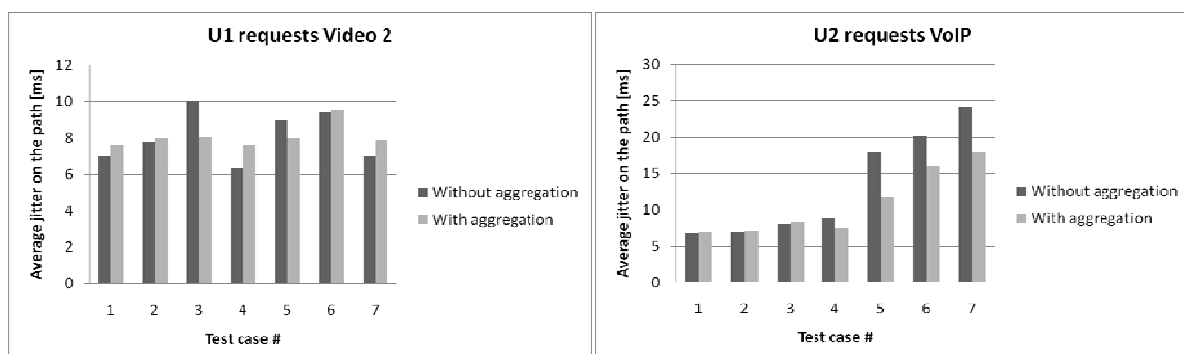


Figure 102: Average jitter on a path for U1 and U2 in case with and without backhaul bandwidth aggregation

3.13.3 Conclusions

By using multiple paths, we can achieve better utilization of the available backhaul resources and increase the overall capacity of a given WMN. Aggregated backhaul bandwidth, made available to a particular AP, can increase access capacity of that AP several times when compared to the capacity achieved through the best available single path. These results are expected. However, legacy multipath approaches for WMNs tend to impose more problems than benefits. Packet reordering problems (directly increasing packet loss) and jitter related problems of multipath routing made these protocols practically unusable in real WMN deployments. The proposed algorithm provides the same level of backhaul bandwidth aggregation with drastically increased QoS levels. Packet reordering problems are provided with described application profile awareness. Results of experiments conducted in the open platform WMN test-bed show that jitter levels tend to be lower and more stable (less fluctuation in their values) in comparison with single path routing. Therefore, next to providing better load balancing and increased WMN bandwidth capacity (better bandwidth utilization), the proposed multipath routing algorithm provides QoS capabilities comparable (in many cases better) to those of single path routing.

3.14 UE-to-UE Trusted Direct Path

3.14.1 Performance evaluation planning

3.14.1.1 Metrics to illustrate the performance of the algorithm

The following performance metrics are considered and being implemented:

- Convergence time versus number of candidate nodes
- Stability of the decision-making outcome with regard to variability of measurements
- Probability of serving actual QoS requirements

3.14.1.2 Benchmark references

Traditionally, the AP is pre-configured; therefore channel selection is performed by the AP for WLAN creation. Here, the proposal addresses the case where neither AP nor channel is known in advance. Furthermore, in our use case, each candidate station can be configured as AP. In our knowledge, there are no direct benchmark references for the complete framework with which to compare the results.

3.14.1.3 Evaluation platform and model

The algorithm is currently under evaluation in Matlab/Simulink environment and with real life measurements: given a set of mobile phones, we perform measurements under various network topologies, these measurements are used as input in Matlab/Simulink environment which, after performing the algorithm, provides the optimal (AP, channel) duplet choice and the minimum required transmit power to reach given QoS requirements.

3.14.2 Performance evaluation results

The 1st phase of evaluation has been based on limited set of situations but with real life measurements. Please see below in Figure 103 to Figure 106 two sample situations, associated measurements and decision.

In sample situation 1, the best AP is **STA4**, the channel is **Channel 5 (2.462 GHz)**, the transmit power to reach QoS is **-20 dB**. In sample situation 2 the best AP is **STA1**, the channel is **Channel 4 (2.462 GHz)**, the transmit power to reach QoS is **-20 dB**

So this early phase of evaluation is limited to functional verification and measurement collection.

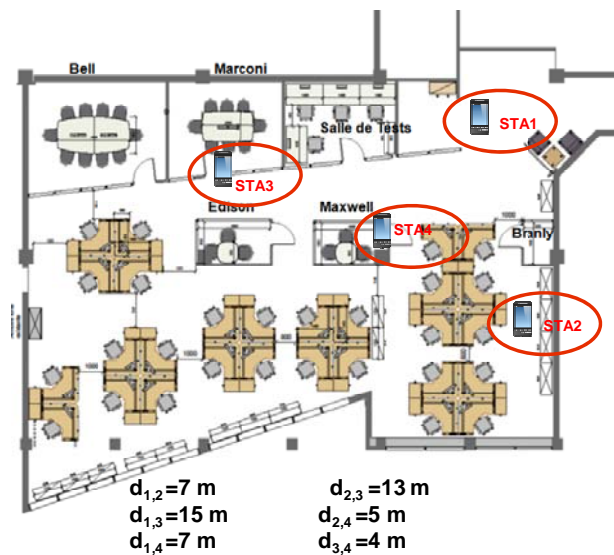


Figure 103: Sample situation 1

Station Candidate 1		Station Candidate 2	
Channels (GHz)	Signal Strength [dB]	Channels (GHz)	Signal Strength [dB]
2.412	-54	2.412	-54
2.437	-67.89	2.437	-80.99
2.442	-58.97	2.422	-70.7876
2.457	-86	2.457	-80
2.462	-74.41	2.462	-67.4904

Station Candidate 3		Station Candidate 4	
Channels (GHz)	Signal Strength [dB]	Channels (GHz)	Signal Strength [dB]
2.412	-55	2.412	-55
2.437	-70.47	2.437	-73.00
2.442	-57	2.442	-65.85
2.457	-49	2.457	-85
2.462	-76.1490	2.462	-78.46

Figure 104: Results for sample situation 1

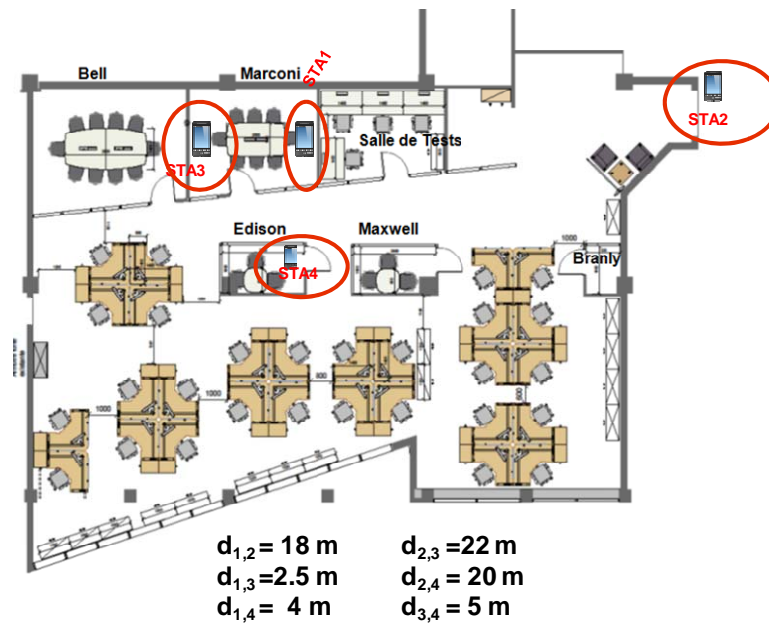


Figure 105: Sample situation 2

Station Candidate 4		Station Candidate 2	
Channels (GHz)	Signal Strength [dB]	Channels (GHz)	Signal Strength [dB]
2.437	-73.361	2.437	-71.79
2.442	-58	2.442	-71
2.452	-51	2.452	-71
2.462	-77.3255	2.462	-74.60

Station Candidate 3		Station Candidate 1	
Channels (GHz)	Signal Strength [dB]	Channels (GHz)	Signal Strength [dB]
2.437	-76	2.437	-73.46
2.442	-56	2.442	-60
2.452	-47	2.452	-56
2.462	-74.69	2.462	-74.87

Figure 106: Results for sample situation 2

3.14.3 Conclusions

The algorithm is implemented and run under static conditions with a limited of situations. The next steps are for finalizing the choice and implementation of the metrics and for running larger numbers of simulation to gather/extract the chosen metrics.

3.15 Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

3.15.1 Performance evaluation planning

3.15.1.1 Metrics to illustrate the performance of the algorithm

The algorithm will be validated using the following metrics:

- Increase in streaming capacity of the underlying WMN for different content delivery approaches (see benchmark references).
- Impact of available storage space on WMN APs on system performance.
- Accuracy of the proactive content placement.
- Stability of the content placement solution with respect to the users' mobility.

3.15.1.2 Benchmark references

Benchmarking references for the proposed algorithms are:

- Content delivery from centralized/dedicated server located in the core side of the network.
- Content delivery form WMN APs where these APs have the ability to deliver requested content only to directly connected end users. If the AP, to which end user is connected, doesn't have the requested content in its cache, user's request will be addressed by the centralized server.
- Random, context unaware proactive content placement. With this analysis, importance of context awareness for proactive content placement will be showcased.

3.15.1.3 Evaluation platform and model

Demonstration will address OneFIT's scenario 5 "Opportunistic resource aggregation in the backhaul network". The addressed use case is "Opportunistic aggregation of backhaul storage resources". Demonstration platform includes (see Figure 107):

- Wireless mesh network (WMN) test-bed with open platform access points (APs) based on MikroTik router-boards and OpenWRT system.
- Database of contextual information.
- Content delivery server (file server and/or video streaming server).
- Simple network management protocol (SNMP) for network monitoring and contextual data gathering.
- Terminals for making requests for content.

In this demonstration the practicality of multimedia content placement on WMN nodes is verified. Two approaches for practical implementation are tested. In the first one, every open platform WMN node is configured as proxy for particular packets representing requests for multimedia content. The mini proxy servers will intercept the user's request for content, inspect it and, if the requested content is locally stored in the WMN node, deliver it to the requesting user using the HTTP download protocol. If the content is not locally available, the request is forwarded to the central content origin

server. The second approach includes the centralized CDN service management server to which all of the user's requests are forwarded. The centralized management server processes the request against the set of contextual parameters which are available in the centralized context database (centralized management server knows where are the copies of the content within the WMN). The most appropriate WMN node is selected for delivery and its URL is sent to the user in order to establish a HTTP transfer of the multimedia file. These two practical approaches are tested in the WMN test-bed comprising of three WMN nodes. A more detailed analysis requires larger test-bed and established core CDN service. The practical results indicate that the first approach (with proxy servers at APs) will require significant modifications to the system software of the WMN nodes in order to enable the necessary context awareness. A centralized approach is more scalable since the centralized WMN management system knows the status of the whole WMN and its storage pools and also possesses more processing power which enables derivation of complex contextual calculations resulting in better context awareness and reactivity to context changes.

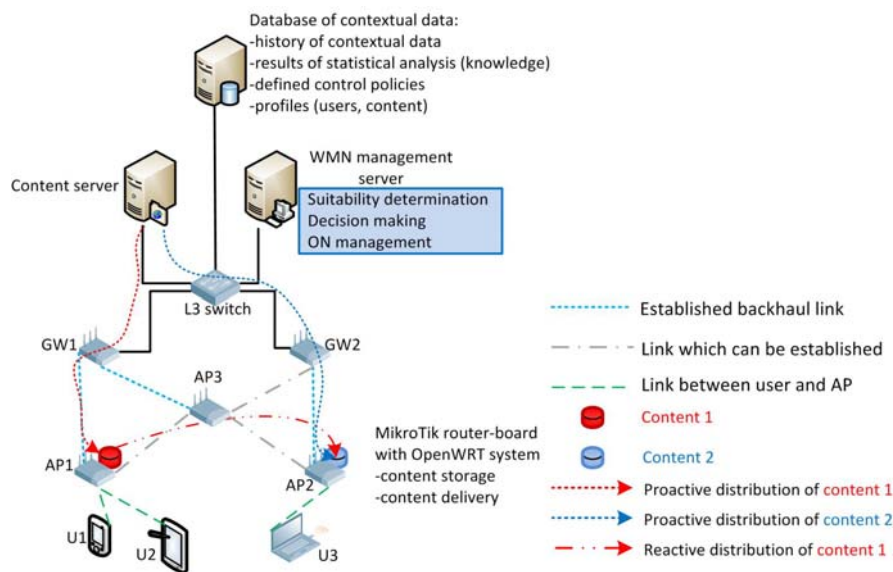


Figure 107: Evaluation platform for backhaul storage resource aggregation

A more detailed simulation campaign is conducted in order to evaluate the MILP model presented in the section 2.14. This model is implemented in Wolfram Mathematica and MathWorks MatLab programming packages. WMN graphs and model parameters are defined in Mathematica and MILP model's matrices are generated. These matrices are forwarded to MatLab where a MILP solver is used for derivation of the optimal solution (node selection). Further analysis of the results is conducted in MatLab. The simulations are performed with WMNs with number of nodes spanning from 10 to 200. Simulations are run on the server station with quad core processor on 3GHz and 12 GB of RAM.

The implemented mathematical model doesn't include any radio environment awareness (channel selection, interference and propagation models). This is due to the fact that these interference related parameters don't have significant impact on selection of nodes for content placement. The assumption is that the underlying WMN management deals with interference throughout the WMN. However, if the WMN management system cannot cope with interference in some regions of the WMN, then WMN graph edges corresponding to links in these regions can be penalized with higher pre assigned weight.

All of the simulated WMN graphs correspond to well designed WMNs. This means that the corresponding network graph of a WMN is connected, nodes have degrees less than some threshold (in our experiments threshold was 6 – node can communicate with maximally 6 neighbours), the number of leaf nodes (with degree equal to one) is limited to 5 percent of total WMN node count

and there is maximally one edge between any two nodes in the network graph (typical practice for 802.11a based backhaul communication).

Simulator is enhanced with inclusion of three different mobility models for end user's: Random Walk, Random Waypoint and the RPGM (reference point group mobility model). As the presented mathematical model evolved (inclusion of new features and constraints) more realistic simulations could be conducted which gave additional weight to obtained results and conclusions.

3.15.2 Performance evaluation results

Mathematical MILP model presented in section 2.14 is implemented in MathWorks MatLab. The results regarding evaluation of impact of different content placement/delivery techniques on total streaming capacity of the WMNs are presented in the following. Also, validation of the MILP model presented in section 2.14 will be shown.

Impact of content placement on appropriately selected WMN nodes on total streaming capacity of the WMN

Analytical simulations in custom simulator (implemented in MathWorks Matlab and Wolfram Mathematica) have shown that total streaming capacity of WMNs can be significantly improved with content placement on WMN nodes and delivery from them to the requesting users. If content redistribution among WMN nodes is enabled then one WMN AP will be able to deliver the requested content to the end users which are not directly connected to that AP. Analytical simulations have shown that this content delivery approach results in total WMN's streaming capacity increase similar to that achieved by introduction of new WMN gateways (GWs) into the WMN deployment. The results of this analysis are presented in [21].

Three content delivery and streaming approaches are tested. First, we will present a content delivery method based on a standard CDN approach, where all of the users' requests are fulfilled from a dedicated content server located in the core network (see Figure 108a). Analysis of this method will show why the WMNs are considered as bottlenecks for content delivery. Next, two methods for streaming of content cached on WMN nodes will be analyzed. We will analyze approach when content, which is stored on WMN APs, can only be delivered to the requesting users who are directly connected to these WMN APs (see Figure 108b). Finally, we will introduce and analyze content streaming solution where content cached on one WMN AP can be streamed to users connected to other APs in the WMN (see Figure 108c). In this approach, a collaborative (p2p based) content delivery among WMN nodes is enabled. For every of the three aforementioned content delivery approaches in WMNs, we have conducted a detailed analysis. Different WMN topology setups and different selections of nodes for content placement/delivery are investigated. This in depth analysis has shown the impact of different system setups on overall content delivery/streaming capacity of the WMNs. The streaming capacity of a WMN is defined as a maximal number of end users who can be served with the selected load at the same time. Different system setups for different WMN graphs are analyzed. Besides investigating the impact of these system setups on streaming capacity of WMNs, analysis is also conducted in order to show how these streaming techniques and system setups impact the ADTL. WMNs in our experiments are presented as network graphs. All experiments are conducted on network graphs corresponding to well designed WMN networks. This means that network graph is connected, nodes have degrees less than some threshold (in our experiments threshold was 6), the number of leaf nodes (with degree equal to one) is limited to 5 percent of total WMN node count and there is maximally one edge between any two nodes in the network graph.

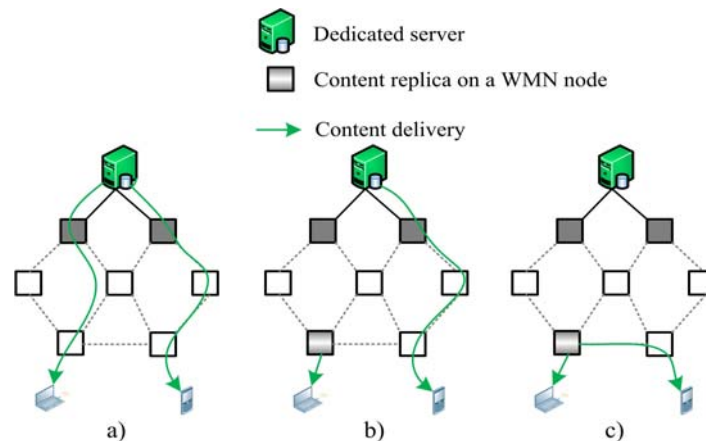


Figure 108: Different content placement/delivery approaches

For clarity of the presentation, the presented approaches will be analyzed on the simple WMN shown in Figure 109. It is considered that every WMN node has two radio interfaces for communication with other WMN nodes (backhaul connections) and one interface for providing access to the end users. A standard 802.11 based WMN is considered. Backhaul communication is done by using the IEEE 802.11a protocol which can provide around 30Mbit/s of user's traffic. Access to the WMN APs is provided over the 802.11g protocol which also provides 30Mbit/s for users' data. If more than two backhaul connections are shown for one WMN node in the network graph, these wireless links will share the total bandwidth provided by two radio interfaces (2x30Mbit/s). We will not address the problems of channel interference and its impact on achievable throughput. 30Mbit/s is considered on every established link between two radio interfaces (if the radio interfaces are not shared with other active links). We will also consider that cable backhaul has an infinite capacity when compared to the capacity of the wireless links (backhaul cable network will not be considered as bottleneck for content delivery). Although our conclusions are made under ideal conditions (no TCP related problems, routing and packet forwarding works perfectly and no interference), the logic behind them is valid for realistic WMN deployments as well. This is because we have focused on impact of WMN topology and delivery node selection changes, which will have the same effect in realistic WMNs as in the simulator's environment.

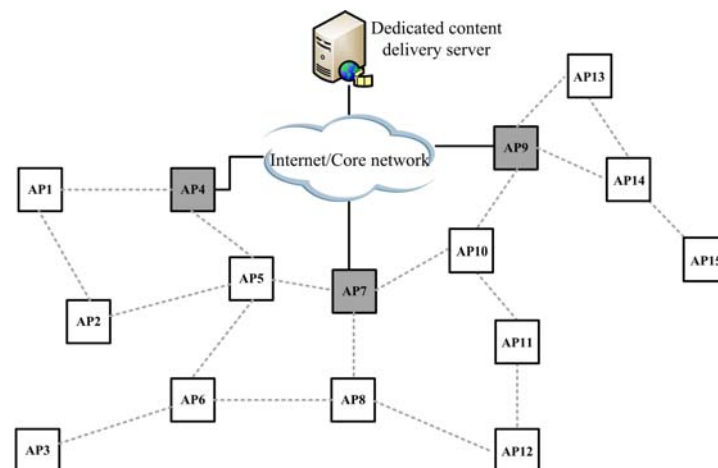


Figure 109: WMN network for detailed analysis (gray nodes – WMN GWs)

In the content delivery approach where all of the content is delivered to the users from a dedicated server, the main impact on the total streaming capacity has the number and position of the WMN GWs since all of the traffic has to go over these nodes. Increasing the number of GW increases capacity of the WMN, however it is also in conflict with the idea of WMN, which is providing the large coverage area with as few as possible stations connected directly to the cable infrastructure.

The great impact on WMN capacity has the GW placement which is dictated by the WMN topology and user distribution. The Figure 110 shows how total streaming capacity of the WMN changes for different combinations of three GWs. Figure 111 shows how total streaming capacity changes with increasing number of WMN GWs. It can be noticed that after certain number of WMN GWs are added, the WMN enters into the saturation regarding the streaming capacity. This saturation is the same as the streaming capacity of the corresponding WLAN.

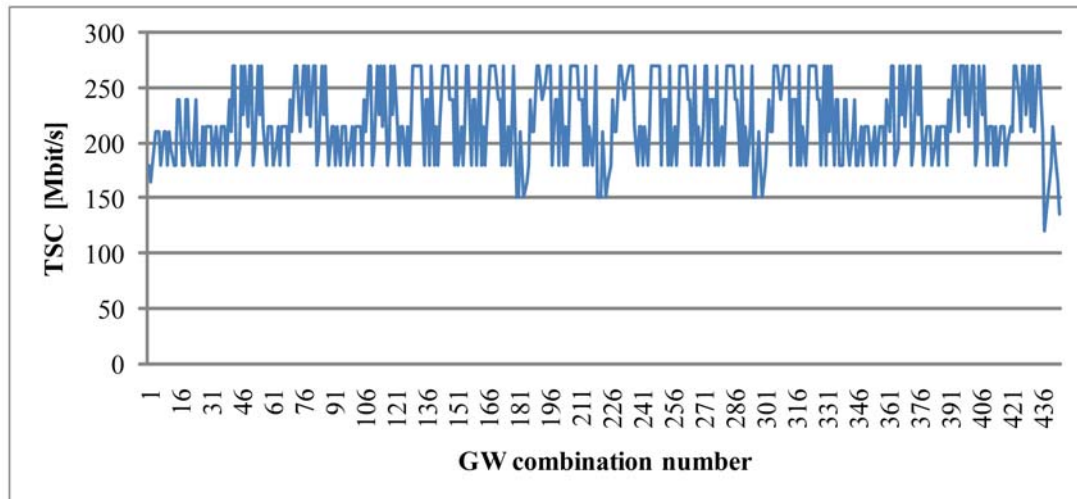


Figure 110: Total WMN streaming capacity for all combinations of three GWs in WMN shown in Figure 109

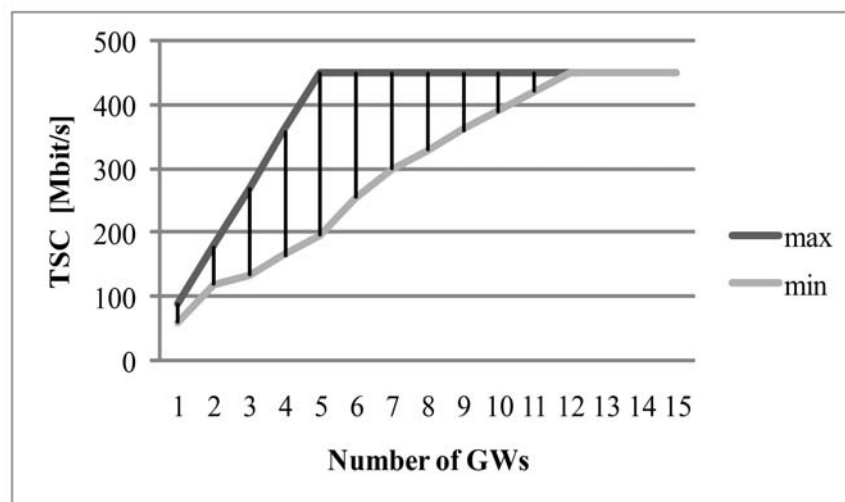


Figure 111: Total streaming capacity of the WMN as function of the number of GWs

Different GW selections will have different ADTLs (Average Delivery Tree Length) defined as the number of wireless hops from source to destination. This parameter will directly impact QoS provided to the end user (increased ADTL is directly proportional to increased delay). Therefore, optimal GW placement can be subject of two optimization criteria, one being maximization of total streaming capacity while the other is minimization of ADTL. As the number of GWs in the WMN rises, ADTL will decrease and when every WMN node is configured as GW, the ADTL will have the value of 1. We haven't considered cable links for the ADTL, since delay over these links can be neglected when compared to delay of the wireless links. Figure 112 depicts ADTL value decrease variations when an additional GW is added into the WMN topology shown in Figure 109. ADTL values are given for every additional GW (from AP1 to AP15 – AP7 excluded as it is the ultimate GW). The results clearly demonstrate dependency of the ADTL value relative to the GW location within a given WMN's constellation. If AP12 is reconfigured into a new GW (in addition to the existing GW-

AP7) ADTL decreases by 0.2. However, if AP14 is configured as a new GW, this will result in an ADTL reduction by 0.6.

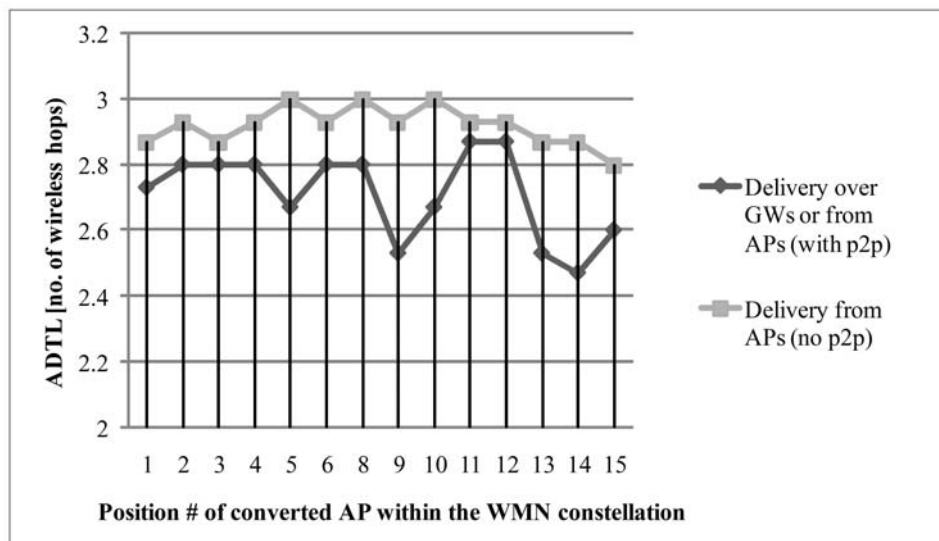


Figure 112: ADTL variations when a specific AP within the analyzed constellation is reconfigured to act as an additional GW or a streaming server

If the content is placed on WMN APs and if it can be delivered only to the requesting users which are directly connected to these APs, the total streaming capacity increases more slowly than when the new GWs are included into the WMN. Figure 113 shows how the total streaming capacity of the WMN shown in Figure 109 changes when content is placed on different number of WMN APs (AP4, AP7 and AP9 are WMN GWs).

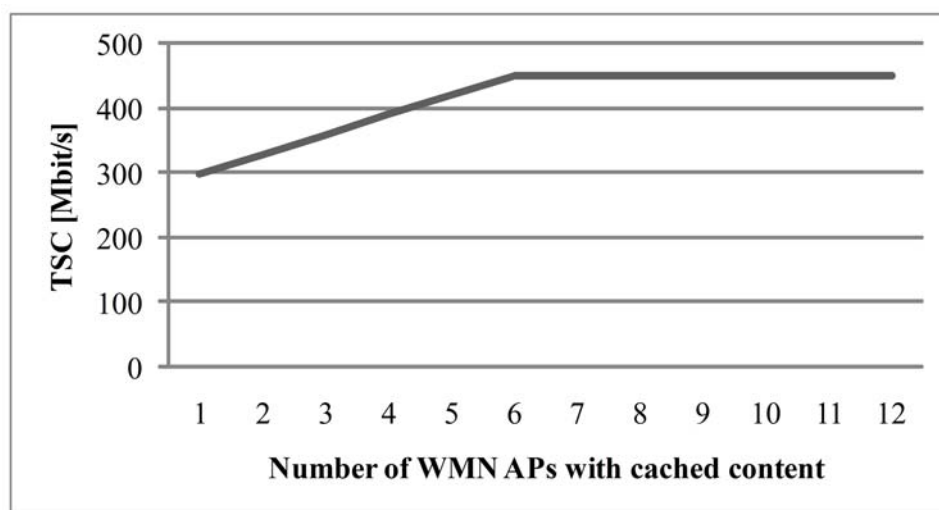


Figure 113: Maximal total streaming capacity values for different number of WMN APs with cached content

Collaborative content delivery among WMN nodes is defined as the ability of the involved WMN nodes with stored content to collectively address the cache misses for the content requests originated from users connected to the other WMN nodes. When the requested content is not stored on the WMN AP to which the requesting user is connected, CDN management system will instruct the optimal WMN AP, which has the content of interest in its cache, to deliver the content to the requesting user. Placing the content on these APs has exactly the same impact on the total streaming capacity as adding the additional GWs. The results from the chart in Figure 111 are valid for this content delivery approach as well. In this case, the minimal and maximal total streaming

capacity values for four GWs can be achieved in WMN shown in Figure 109 with three GWs and content placed on one AP. The optimal AP selection will result in maximal value of total streaming capacity and other APs can provide lower total streaming capacity. Now, we have achieved total streaming capacity increase equivalent of that achieved with additional GWs. Since introduction of new GWs into the existing WMN is a very demanding job (with respect to costs and time consumptions), this content delivery approach presents the best solution for providing CDN over existing WMN. Also, content placement on WMN nodes represents more scalable solution for total streaming capacity increase than adding new GWs. By different content placement strategies on WMN APs, streaming capacity increase can be provided where and when needed.

In order to confirm the conclusion presented here, we present the same analysis for the WMN consisting of 50 APs. In this topology (see Figure 114), there is only one WMN GW. All WMN APs support collaborative content delivery. Content placement on different number of WMN APs and their combinations is evaluated. Number of APs with stored content is increased by one in every experiment until all APs have content stored on them. For every selected number of APs, 40 different combinations of content placement are inspected. This gives the total of 2000 (50 nodes x 40 combinations) results for total streaming capacity of the WMN presented in Figure 114. Box-plot diagram for total streaming capacity results is shown in Figure 115. In this diagram, we can see that maximal and minimal total streaming capacity values follow the same rule as in case where the number of WMN GWs and their combinations are gradually changed (results in Figure 111). The same results, as those shown in Figure 115, are achieved for 50 nodes WMN (see Figure 114) when the number and combination of GWs is changed, thus confirming our conclusion that content placement on WMN AP, with enabled collaborative (p2p) delivery, has the same potential to impact total streaming capacity increase (with respect to given topology and content which is cached on WMN APs) as reconfiguration of that AP into the new GW.

When compared with the second content delivery strategy (where content stored on WMN APs can only be delivered to directly connected end users), the ability of WMN APs to collaborate in order to address each other's cache misses, will provide maximal total streaming capacity with less copies of the content locally stored on WMN APs. This will provide better utilization of storage resources on WMN APs enabling local caching of broader spectrum of different content.

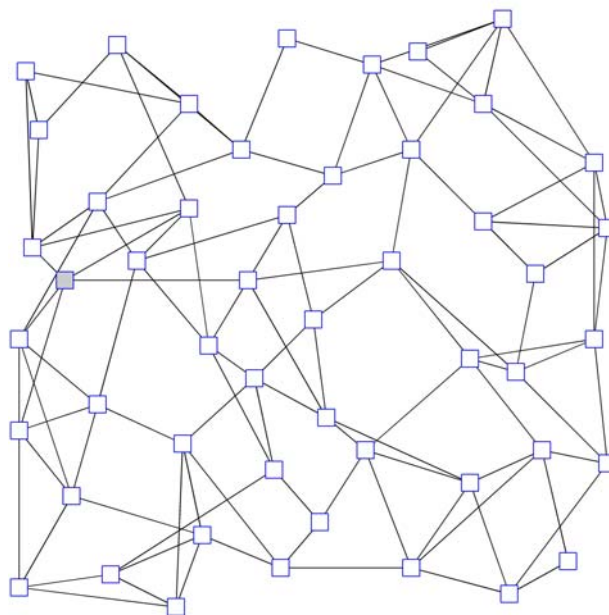


Figure 114: WMN topology composed of 1GW and 49 APs (50 nodes in total)

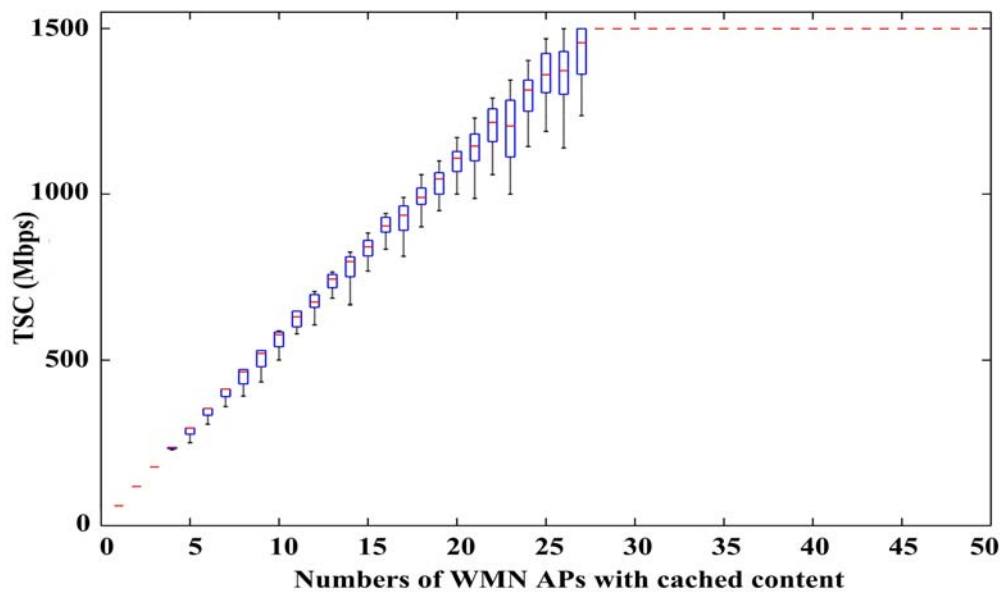


Figure 115: Box-plot diagram of total streaming capacity results for different number and combinations of WMN APs with stored content and p2p delivery enabled (beginning with 27 APs, calculated total streaming capacity values for all experiments are constant and the same, resulting with the absence of box plots)

Performance analysis of the MILP model

The MILP model presented in section 2.14 is implemented in the MatLab and Mathematica software packages. The performance evaluation includes:

- Speed of WMN node selection for content placement;
- Sensitivity to user mobility;
- Recognition of different content placement/streaming techniques;
- Size of the caching storage at WMN APs.

The problem at hand (selection of optimal set of WMN nodes for content placement with respect to the current WMN/CDN service context) is NP hard. However, content placement is not a very frequent event. We can assume that it is performed few times per day (i.e. majority of the users is at work, home and asleep in more or less the same part of the day). In our approach we propose that the content placement is calculated in a well dimensioned centralized management server. Laptop with Core i5 processor on 2GHz and 4GB of RAM took 10.9 seconds to calculate the content placement strategy across WMN network with 100 station and 100 user nodes. The same problem was solved on a server machine with 3GHz quad core Xenon processor and 12GB of RAM in 6.7 seconds. Larger problems (200 station and 300 user nodes) took around 4 minutes for solving on laptop and 3.4 minutes on server machine. In practice WMN larger than 200 nodes can be subdivided into smaller clusters grouped based on location and content placement can be calculated for every cluster separately thus decreasing the calculation time.

The three content streaming/placement strategies described above are named **nocache** (delivery from centralized server), **cache-ap** (access points can cache content and deliver it to directly connected users) and **cache-p2p** (access point can cache content and deliver it to any user in the WMN). Topology of CDN (Graph) is the same for all of the presented experiments. There are three mobility models under the same graph entity. For each mobility model, there are three cache types.

For nocache scenario, there is no further branching; however, for cache-ap and cache-p2p, there are more cases, one for each cache size.

Experimental setup for evaluation of the MILP model sensitivity on selected contextual changes (user mobility, AP cache size, different content placement and streaming approaches):

- Network graph consists of 50 nodes, where one is acting as a GW, and the others are APs.
- Network graph covers an area of 1000mx1000m.
- There are 7 files with 3 different qualities encoded using 0.5Mbps, 1Mbps and 2Mbps.
- Total content of the network is around 370MB
- 30 users are moving and requesting files.
- User movements are modelled using 3 mobility models:
 - Random Walk
 - speed from 0 to 10km/h
 - direction 0 to 2π
 - movement duration of 60 seconds
 - Random Waypoint
 - speed from 0 to 10km/h
 - pause time from 0 to 30 seconds
 - RPGM (reference point group mobility model)
 - speed from 0 to 10km/h
 - pause time from 0 to 30 seconds
 - with 6 groups of 5 members per group
- Maximal link load is 30Mbps.
- Maximal total load for APs is 30Mbps.
- Maximal total load for GWs is 60Mbps.
- Sizes of APs caches used in experiments are 50MB, 100MB, 200MB and 300MB
- Simulation time is 900x2 seconds.

Experimental results presented in Figure 116 to Figure 121, show that the MILP model selects the appropriate content distribution among WMN APs when the selected contextual parameters are changing. The results regarding advantage of **cache-p2p** content streaming/placement method are clear from the showed results. The difference between different content streaming/placement approaches stays visible when the relevant contextual parameters are changing.

3.15.3 Conclusions

Giving short interpretation of results, one can notice:

- obvious advantage of cache-p2p organization of WMN CDN (the bigger cache capacity – the better performance, with respect to all observed indicators of network behaviour);
- presented MILP model is robust (not sensitive) with respect to different user mobility models, since the difference in corresponding indicators under 3 mobility models is not very high. Only under RPGM group mobility model, the peaks are more expressed due to heaviest network load generated by the groups of users;
- content provider can save costs with the same QoS – for an example, on Figure 116 (ADTL), one can notice how cache-ap/size-200 has almost the same performance as cache-p2p/size-100 (almost overlapping lines). Using smart caching/content placement algorithms, observed features can be further improved (for an example, if local groups of nearby APs contain complementary content, whose union is almost (or to some extent) the copy of source server's content);

At the end, shown results are collected from “regular” scenarios, but using the presented MILP model one can examine different experimental setups, modelling and detecting “corner cases” and irregular situations in (parts of) WMN CDN.

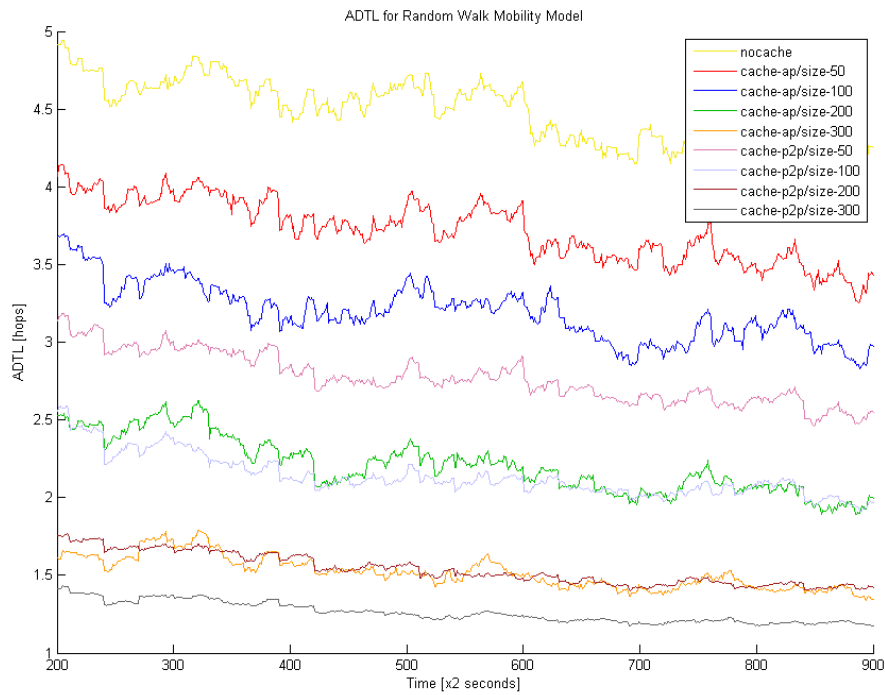


Figure 116: ADTL with random walk mobility model

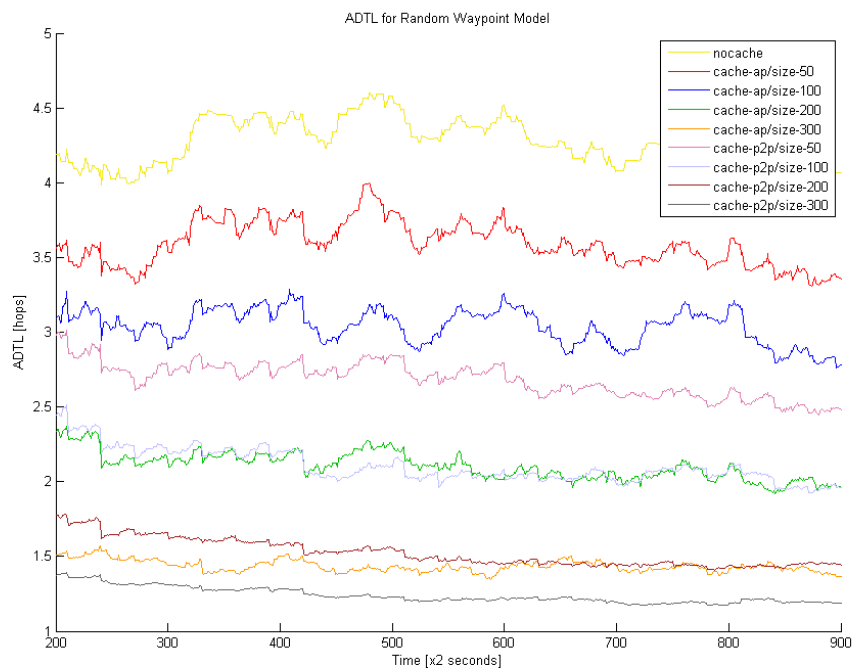


Figure 117: ADTL for random waypoint model

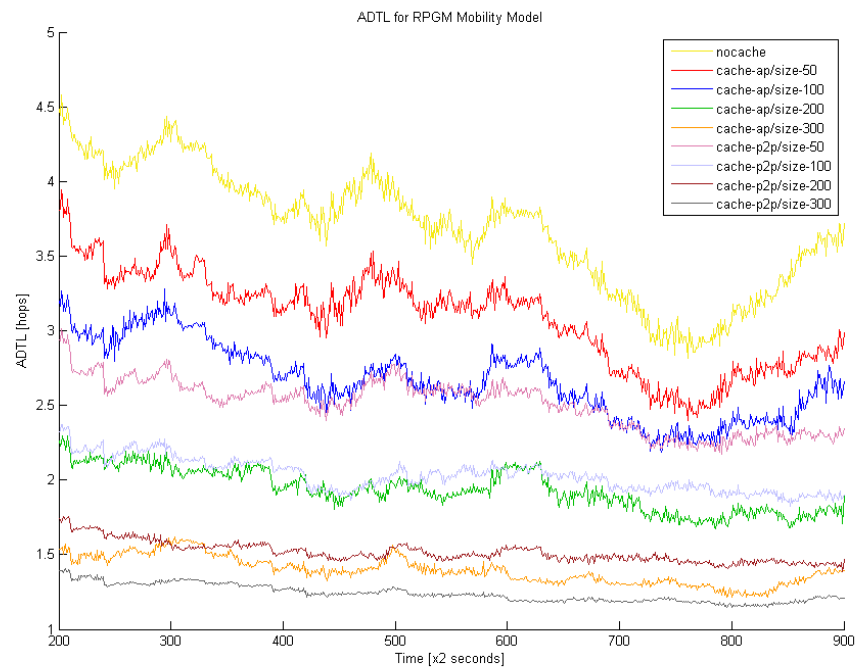


Figure 118: ADTL for RPGM mobility model

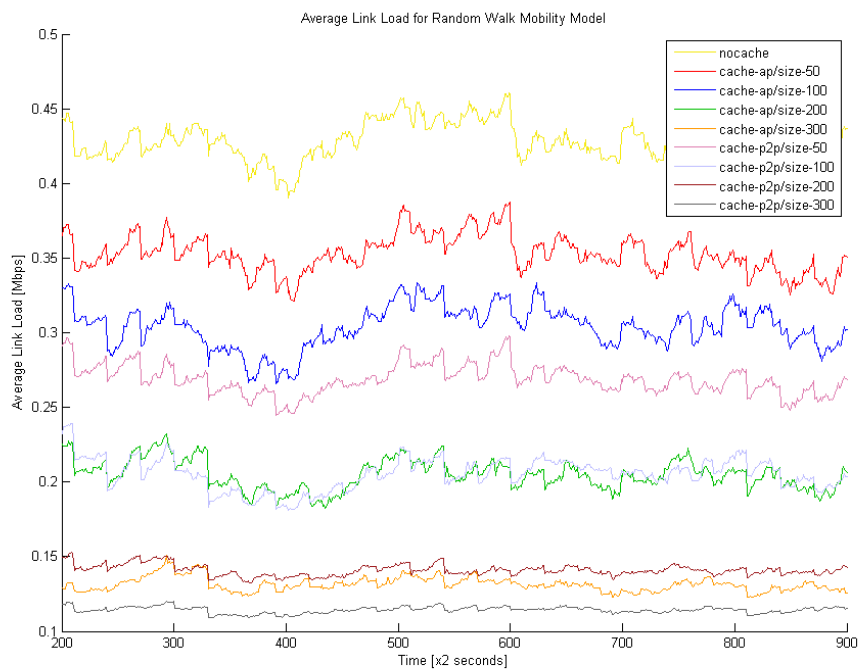


Figure 119: Average backhaul link load for random walk mobility model

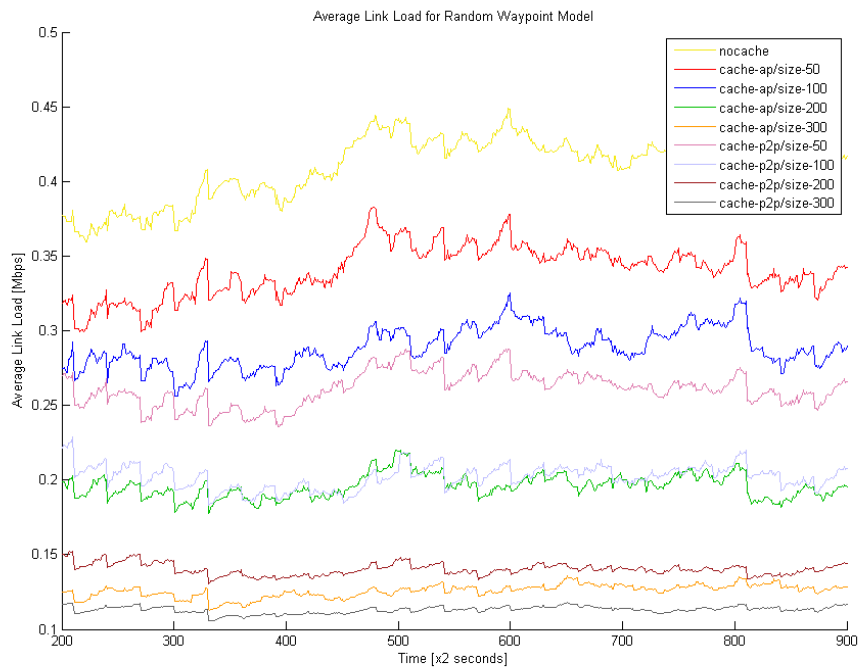


Figure 120: Average backhaul link load for random waypoint model

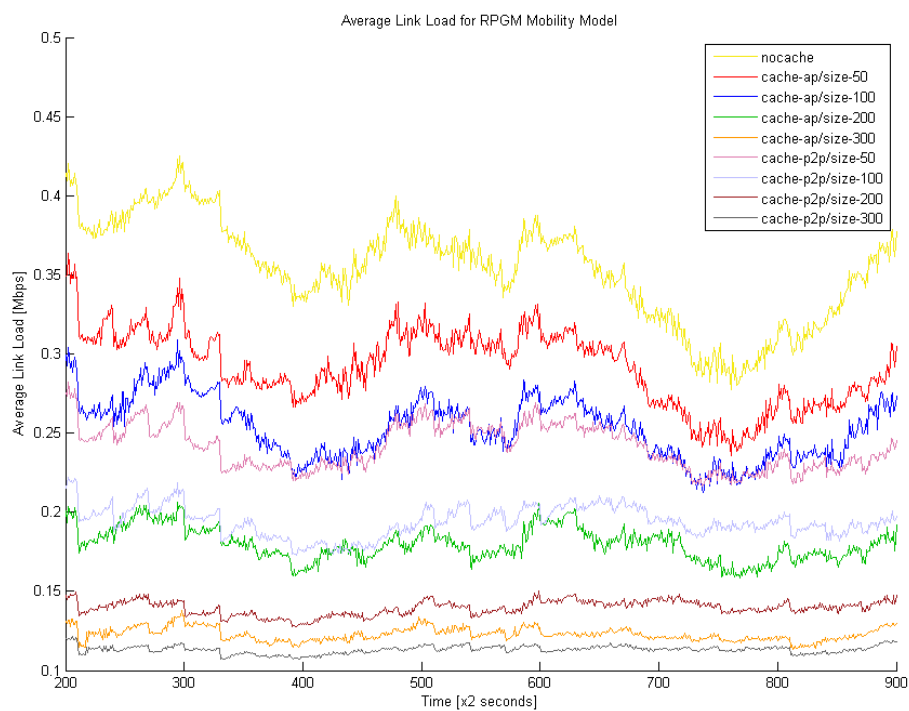


Figure 121: Average backhaul link load for RPGM mobility model

3.16 Capacity Extension through Femto-cells

3.16.1 Performance evaluation planning

3.16.1.1 Metrics to illustrate the performance of the algorithm

Performance evaluation is based on the following metrics which reflects the energy efficiency and the QoS offered to the users of the ON:

- Power level of femtocells: The transmission power of each femtocell, measured in Watts.
- Load: The load of the macro BS and the femtocells, in terms of bps. The target is not only to relieve the BS, but also not to overload the femtocells.
- Terminals QoS: The QoS that is assigned to each terminal, in terms of bps.

3.16.1.2 Benchmark references

The following meta-heuristic algorithms are utilized in order to compare their solutions with the one provided by the DRA algorithm:

- Simulated Annealing [18]
- Tabu Search [19]

These algorithms have received a very positive feedback from the network community because of their proved ability to provide good solutions in a logical amount of time, as well as the ability to be applied in the most up-to-date network problems.

3.16.1.3 Evaluation platform and model

The algorithm is evaluated through simulations at the OneFIT prototyping platform described in [10]. The simulator generates traffic and creates a hotspot at the macro BS. Furthermore, the simulator utilizes the propagation model that is described in [9]. The path loss is calculated through the following equation:

$$PL = 43.85 \cdot \log(f) - 4.78 \cdot \log^2(f) + 20 \cdot \log(d) - 83.36 + 10 \cdot \log(\Theta) \quad (93)$$

Where f is the frequency at which the femtocell operates, d is the distance between the femtocell and the terminal, while Θ represents the lognormal fading.

The algorithm is executed to the CMON agent of the BS and an ON is created that redirects a number of macro-terminals to the femtocells and power levels are allocated to the femtocells. Furthermore, regarding the energy benefits that derive from the DRA concept, a customized version of the ONE simulator [11] was utilized.

3.16.2 Performance evaluation results

3.16.2.1 Dynamic Resource Allocation to femto-cells

The topology that is used for the evaluation of the DRA algorithm consists of a macro BS that will face congestion issues. In addition, 7 femtocells are considered within the area of the BS with maximum transmission power of 120 mW. Moreover, it is assumed that they can be configured to operate at 6 power levels, i.e. 50, 60, 70, 80, 90 and 100% of the maximum transmission power and for simplicity reasons when a femtocell is configured to operate at $X\%$ of its maximum transmission power it will be mentioned in the text that it operates at the $X\%$ -power level. Also, the femtocells are considered to be configured to use the CSG model. Furthermore, terminals with power sensitivity of -120 dBm are uniformly distributed within the BS area. Regarding the SA algorithm, the cooling rate is set to 0.85 and the initial temperature is set to 100 degrees, while for the TS algorithm the memory size of the Tabu List is set to 15. Figure 122 presents a snapshot from the

evaluation platform. The hexagon represents the macro BS while the circles depict the femtocells. The inner circles correspond to the initial coverage of the femtocells, i.e. when they are transmitting at the minimum power level, while the outer circles correspond to the final coverage of the femtocells.

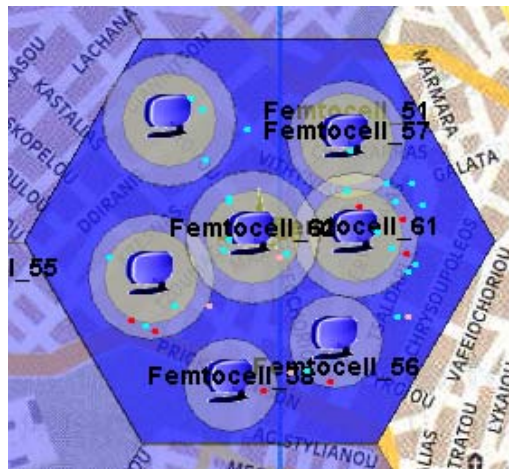


Figure 122: Network topology

Figure 123 illustrates a comparison of the DRA algorithm's solution with the ones of the SA and the TS. Part (a) illustrates the power levels that are allocated to the femtocells by each algorithm, while part (b) depicts the number of terminals that each femtocell acquired after the allocation of the power levels. As far as the DRA algorithm is regarded, femtocell 55 that was configured to operate at the 80%-power level acquired the most terminals (4 terminals). In addition, femtocell 61 that was configured to operate at the 100%-power level acquired 3 terminals. Furthermore, femtocells 56, 57 and 62 that were configured at the 60%-power level acquired 1, 1 and 2 terminals respectively, while femtocell 51 that was configured to operate at the 50%-power level acquired 1 terminal. Terminal 58 that did not acquire traffic was configured to the 50%-power level also.

As far as the SA algorithm is regarded, femtocell 55 that was configured to operate to the 90%-power level acquired the most terminals (5 terminals). Femtocell 55 was also the femtocell that acquired the most terminals by the DRA algorithm. Moreover, femtocells 51 and 56 that were configured to operate at the 80%-power level acquired 1 terminal, while femtocells 58 and 61 that were configured to operate at 60%-power level acquired 1 terminal as well. On the other hand, femtocells 57, 58 and 62 that acquired no traffic, were configured to operate at 50%, 60% and 60%-power level respectively.

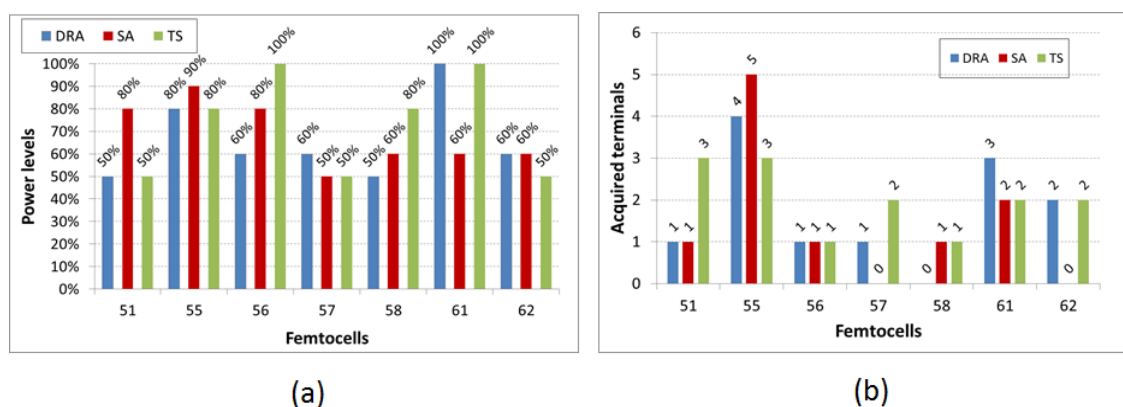


Figure 123: (a) Power allocation to femtocells, (b) acquired terminals by each femtocell

Regarding the solution provided by the TS algorithm, femtocell 55 as in the previous algorithms was the one that acquired the most terminals (5 terminals) and was configured at the 80%-power level.

Femtocells 56 and 61 that were configured to operate at the maximum power level acquired 1 and 2 terminals respectively, while femtocell 58 that was configured at the 80%-power level acquired 1 terminal. Moreover, femtocells 51, 57 and 62 that were configured to the minimum power level acquired 3, 2 and 2 terminals respectively.

Figure 124 depicts a quality comparison of the solutions that are computed by each algorithm. The primary horizontal axis, i.e. the bottom one, presents the number of iterations for the DRA algorithm, while the secondary horizontal axis, i.e. the top one, depicts the number of iterations of the SA and the TS algorithms. In addition, the vertical axis presents the OF values of the algorithms for each iteration. Regarding the DRA algorithm, at the first iterations the value of the OF is high since the femtocells have not acquired enough traffic to relieve the BS. However, as the algorithm progresses in relation with time, the OF value decreases as better solutions are constructed. As the algorithm reaches to an end, the OF value increases again since most terminals have been covered by the femtocells and the power level of the femtocells increases without covering more users. At the final iteration, the OF value decreases again as the femtocells are configured to operate to the last power-level to which they acquired terminals. Apparently, the DRA algorithm managed to compute the best solution with OF value of 23.01, while the OF value of the best solution of the SA was 24.14 and the best OF value of the TS was 23.54. Therefore, the quality of the DRA solution proved to be 4.68% better than the one of the SA and 2.27% better than the one of the TS. In addition, the quality of the TS solution proved to be 2.46% better than the one of the SA.

Moreover, as it can be observed, the progress of the SA OF values presents higher fluctuation than the one of the DRA and the TS algorithms. The reason is that the TS algorithm constructs a neighbour area based on the previous selected solution at each iteration and then selects the best solution of this neighbourhood. Regarding the DRA algorithm, at each iteration the power level of only one femtocell is alternated which leads to small changes to the values of the OF.

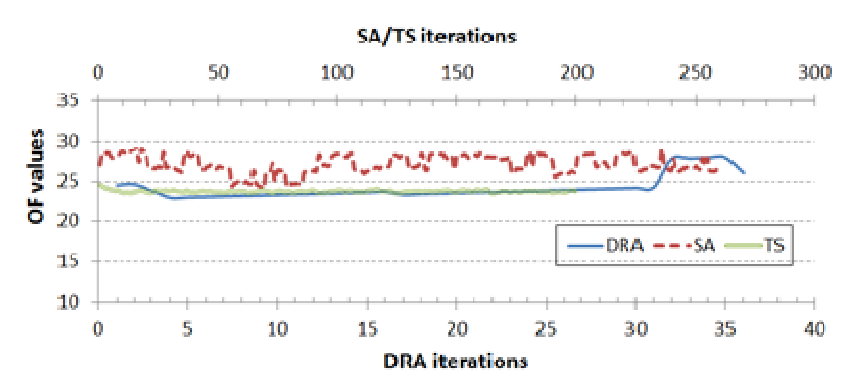


Figure 124: OF progress of the DRA and the SA algorithm

Figure 125(a) illustrates a comparison of the runtime that the DRA, the SA and the TS algorithms needed to compute the solution. The runtime for the DRA was 8876 ms, while the SA needed 12132 ms to estimate the sub-optimal solution and the TS algorithm needed 196790 ms. Therefore, the DRA algorithm proved to be 36.68% faster than the SA and 2117.10% faster than the TS. In addition, the SA was 1522.07% faster than the TS. The reason is that the DRA algorithm splits the initial problem to sub-problems that are processed in parallel and achieves maximum CPU utilization. On the other hand, the TS algorithm maintains the Tabu List and needs to compare the generated solutions with the ones of the Tabu List in order to identify whether a solution is tabu which is a high time consuming process.

Figure 125(b) presents the number of iterations that each algorithm needed to estimate its sub-optimal solution. The DRA algorithm needed 36 iterations, while the SA and the TS algorithms needed 259 and 200 iterations respectively.

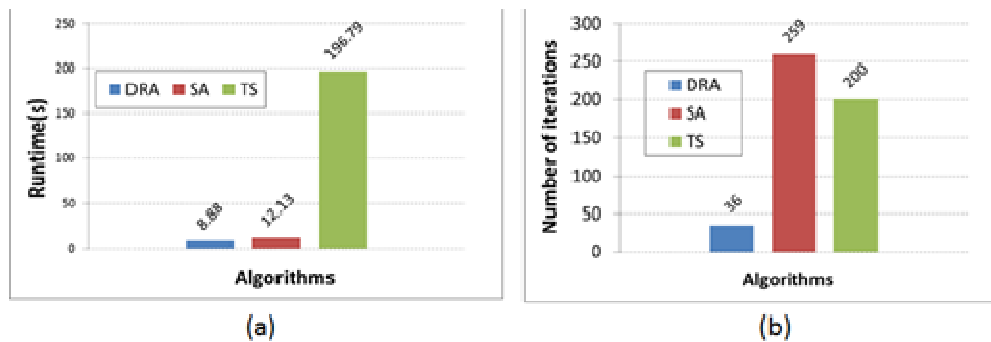


Figure 125: (a) Runtime and (b) number of iterations needed for the DRA, SA and TS algorithms.

Figure 126(a) illustrates the progress of the normalized load of the macro BS before and after the solution. The normalized load is the sum of the load of the macro-terminals divided by the capacity of the BS. Firstly, traffic increases as more terminals arrive to the BS. At some point a hotspot is created and the macro BS faces congestion issues since its normalized load remains above 70%. The solution mechanism is triggered and as soon as the solution is applied the load tends to decrease.

In a similar manner, Figure 126(b) depicts the progress of the normalized load of a femtocell. As soon as the solution mechanism is triggered and the femtocell acquires traffic, its load increases but not to such a level that will cause congestion to the femtocell.

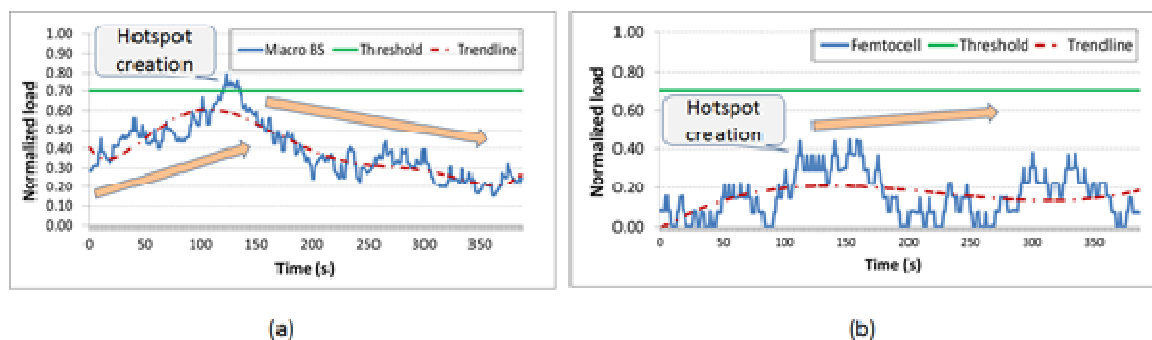


Figure 126: Normalized load of (a) the macro BS and (b) a femtocell before and after the solution

3.16.2.2 Energy efficiency through the opportunistic exploitation of femto-cells

In order to evaluate the energy benefits that derive from the proposed concept, 3 test cases are considered for estimating the power consumption of the macro BS. The values of the parameters that were considered during the simulations are depicted in Table 10.

Table 10: Simulation parameters

Parameter name	Parameter value
BS antenna height	20m
Terminal's antenna height	1.6m
Frequency of transmission	2000 MHz
Terminal's sensitivity	-120 dBm

The topology that is used for the evaluation of the proposed solution consists of a macro BS, 30 femtocells that are located in a uniform distribution within the area of the BS and 50 terminals that move randomly within the area of the BS with an average velocity of 1 m/s.

Test case 1 illustrates the impact of enabling femtocells to the network, to the power consumption of the macro BS, while Test case 2 aims at showing how the number of users affects the power consumption of a macro BS. Finally, Test case 3 depicts the impact of the use of femtocells to the battery lifetime of a terminal.

These test cases are indicative scenarios that highlight the benefits that derive from the concept of the capacity expansion through femtocells.

Test case 1

In this test case, the impact of the number of femtocells on the power consumption of the BS will be examined. Therefore, a macro BS area is considered as shown in Figure 127(a). The outer circle depicts the coverage of the macro BS, while the smaller circles indicate the coverage of the femtocells. Firstly, the case where the BS operates without nearby femtocells will be studied and then 10 femtocells will be enabled each time. The simulation time was 2000 secs.

Figure 127(b) depicts a snapshot from the case where all terminals are connected to the BS and all femtocells are disabled, while Figure 128 illustrates the total energy consumption of the BS. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. As it can be observed, the number of terminals that are connected to the BS is constantly 50 due to the fact that there are no nearby femtocells to acquire terminals.

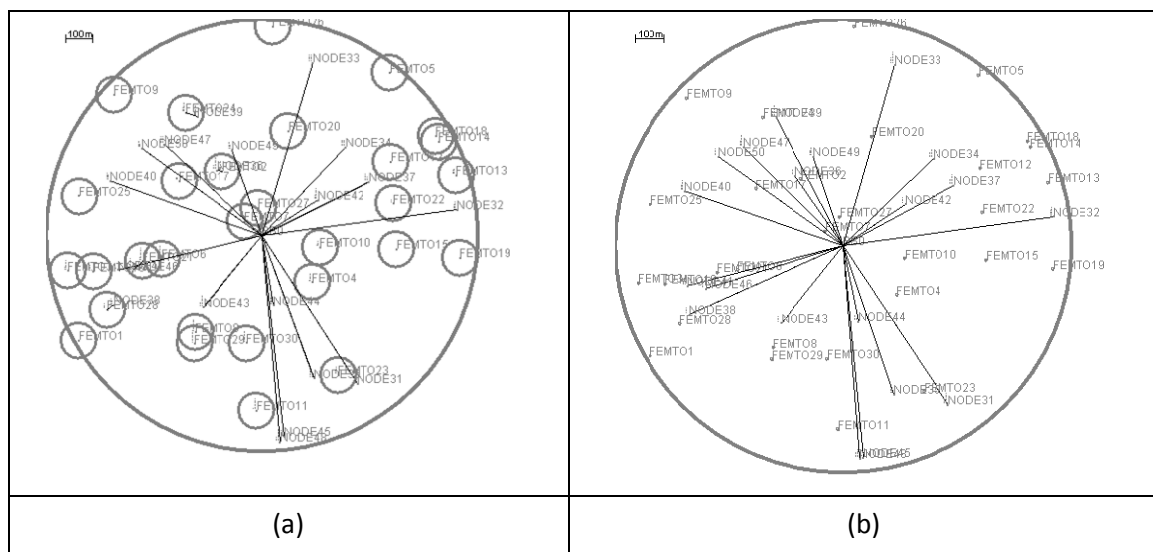


Figure 127: A macro BS (a) with and (b) without femtocells within its coverage

Figure 129 illustrates the progress of the transmission power of the BS. The horizontal axis depicts the simulation time and the vertical axis on the left depicts the transmission power of the BS. The black line depicts the moving average of the transmission power of the BS. As it can be observed, when more terminals are transmitting data, the transmission power is high, while when most terminals are idle, the transmission power is very low.

Figure 130 depicts a snapshot from the case of the macro BS with 10 nearby femtocells, while Figure 131 illustrates the total energy consumption of the BS with 10 nearby femtocells. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. Apparently, the energy consumption of the BS decreased due to the fact that the femtocells

acquired a proportion of the traffic of the macro BS. In addition, as it can be observed the number of terminals that are connected with the BS has reduced since a proportion of the terminal is served by the femtocells.

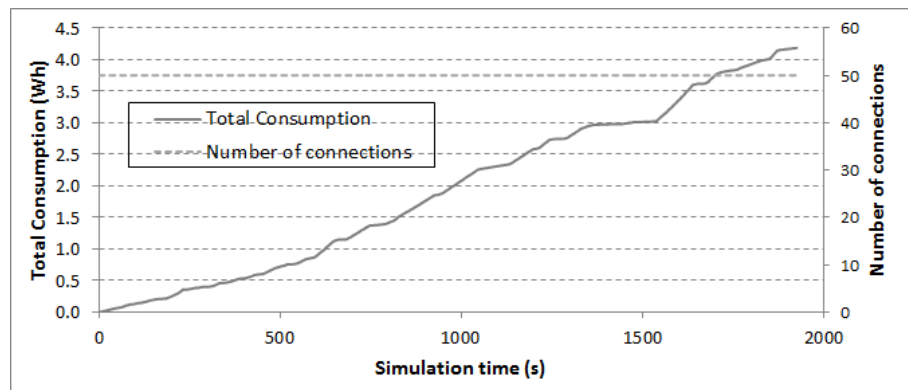


Figure 128: Total energy consumption of a BS without femtocells

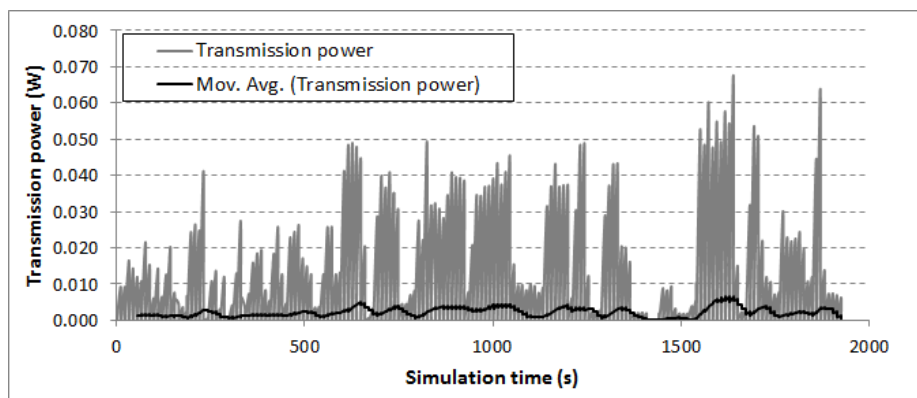


Figure 129: Transmission power of the BS without femtocells

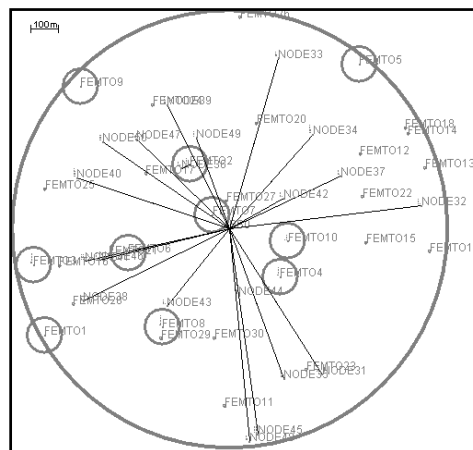


Figure 130: A macro BS with 10 nearby femtocells

Figure 132 illustrates the progress of the transmission power of the BS. The horizontal axis depicts the simulation time and the vertical axis on the left depicts the transmission power of the BS. The black line depicts the moving average of the transmission power of the BS.

Figure 133 depicts a snapshot from the case where 20 femtocells are within the area of the macro BS, while Figure 134 illustrates the total energy consumption of the BS. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. Apparently,

the energy consumption of the BS has decreased even more due to the fact that more femtocells acquired traffic from the macro BS. In addition, as it can be observed the number of terminals that are connected with the BS has reduced more.

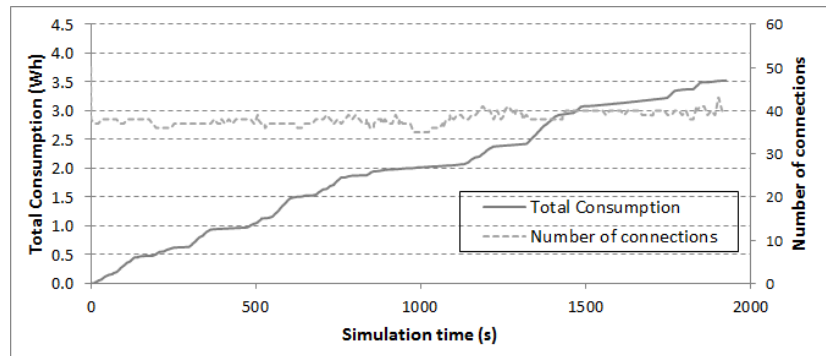


Figure 131: Total energy consumption of the BS with 10 nearby femtocells

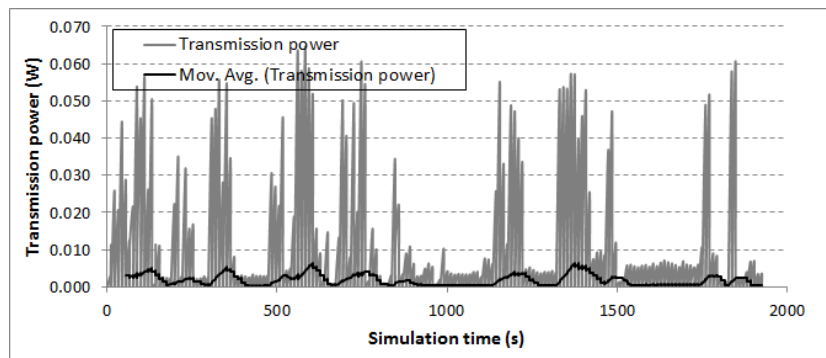


Figure 132: Transmission power of the BS with 10 nearby femtocells

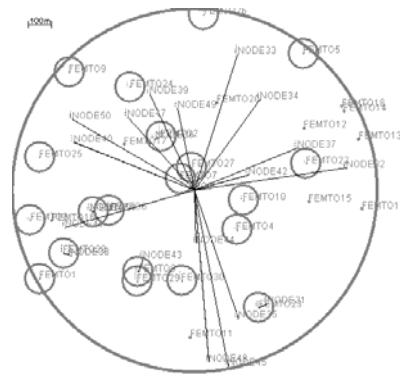


Figure 133: A macro BS with 20 nearby femtocells

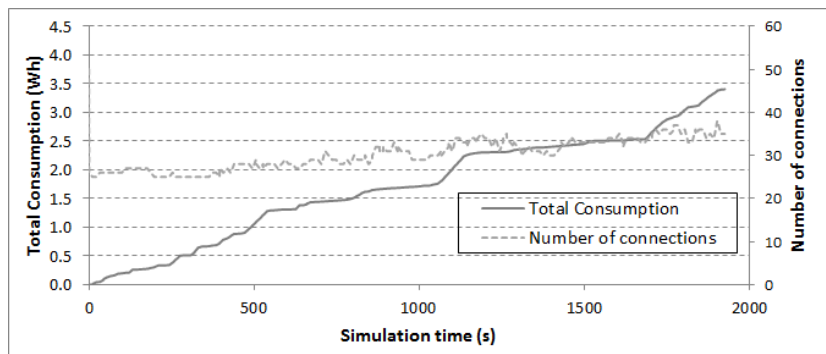


Figure 134: Total energy consumption of the BS with 20 nearby femtocells

Figure 135 illustrates the progress of the transmission power of the BS. The horizontal axis depicts the simulation time and the vertical axis on the left depicts the transmission power of the BS. The black line depicts the moving average of the transmission power of the BS.

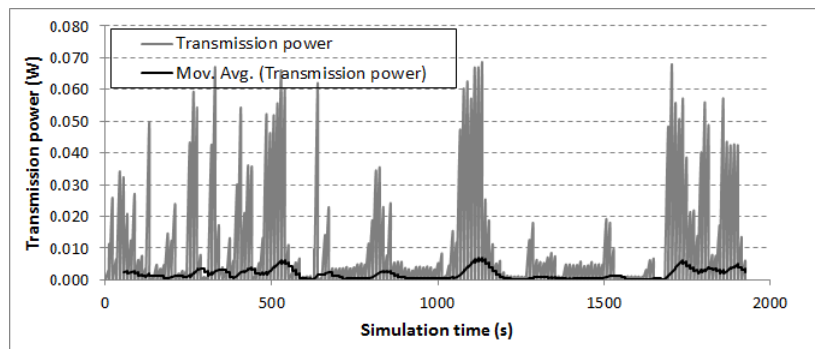


Figure 135: Transmission power of the BS with 20 nearby femtocells

A snapshot of the case of a macro BS with 30 nearby femtocells is depicted at Figure 127. Figure 136 illustrates the total energy consumption of the BS with 30 nearby femtocells. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. In this case, the energy consumption of the BS has not decreased that much in comparison with the case of the 20 nearby femtocells, since most users have been already rerouted to the femtocells.

Figure 137 illustrates the progress of the transmission power of the BS. The horizontal axis depicts the simulation time and the vertical axis on the left depicts the transmission power of the BS. The black line depicts the moving average of the transmission power of the BS.

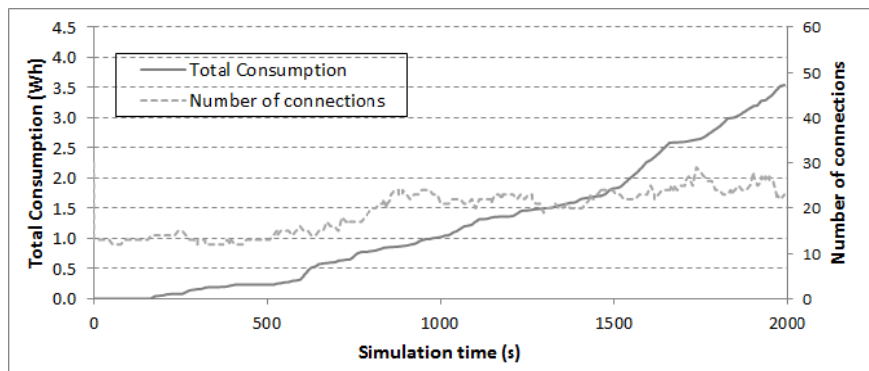


Figure 136: Total energy consumption of the BS with 30 nearby femtocells

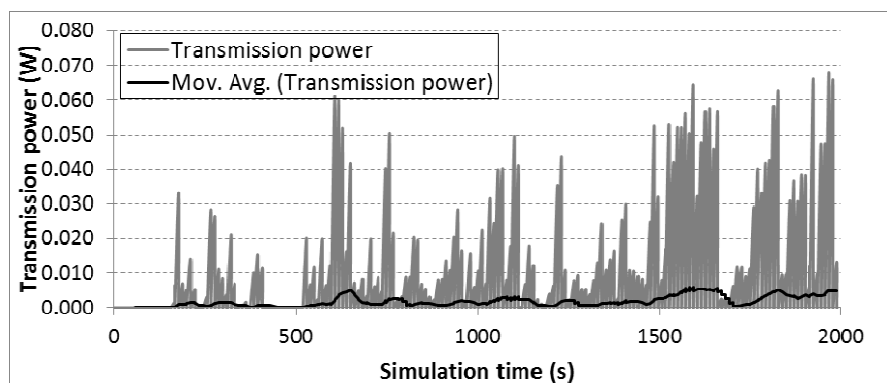


Figure 137: Transmission power of the BS with 30 nearby femtocells

Finally, Figure 138 illustrates a comparison of the energy consumption of the BS for the aforementioned cases. The vertical axis indicates the BS total energy consumption, while the

horizontal axis depicts the network type, i.e. a network without femtocells and with 10, 20 and 30 femtocells. More specifically, when 10 femtocells were enabled to the network the energy consumption of the BS decreased by 18.54%. When 20 femtocells were enabled in the network, the energy consumption of the BS was reduced by 19.72% in comparison with the case where there were no femtocells. Finally, when 30 femtocells were enabled, the energy consumption of the BS was reduced by 20.01% percent. Therefore, as femtocells are deployed to the network, the energy consumption of the BS decreases. However, after a point where most of the traffic has been rerouted to the femtocells, the addition of more femtocells is not that much beneficial.

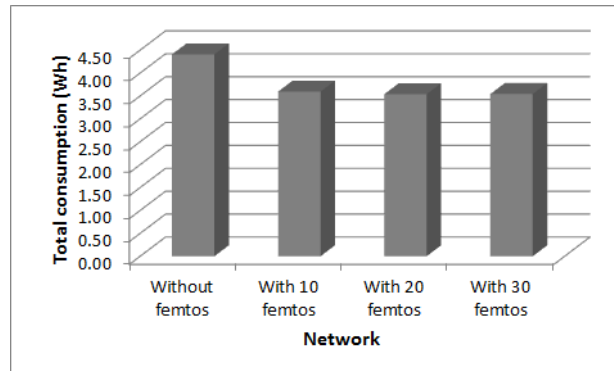


Figure 138: Energy consumption comparison for a BS with 0, 10, 20 and 30 nearby femtocells

Test case 2

In this test case, the impact of the number of terminals on the power consumption of the BS will be examined. A macro BS area with 30 femtocells is considered as in the previous case. The number of terminals for which the BS energy consumption will be studied is 30, 40 and 50 terminals.

Figure 139 illustrates the total energy consumption of the BS with 30 terminals. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. In this case, the energy consumption of the BS is very low since most users are served through the femtocells as can be observed also from the number of terminals that are connected to the BS.

Figure 140 illustrates the total energy consumption of the BS with 40 terminals. The horizontal axis depicts the simulation time, the vertical axis on the left depicts the energy consumption of the BS and the vertical axis on the right depicts the number of terminals that are connected to the BS. In this case, the energy consumption of the BS has increased as it was expected since more terminals were added to the network. Moreover, it can be observed that the number of the connected terminals to the BS has also increased.

The total energy consumption of the BS for the network that comprises 50 terminals is illustrated at Figure 136 of Test case 1. As it can be seen, the energy consumption of the BS is even higher since 10 additional terminals were included in the network. In addition, the number of terminals that are connected with the BS was increased respectively.

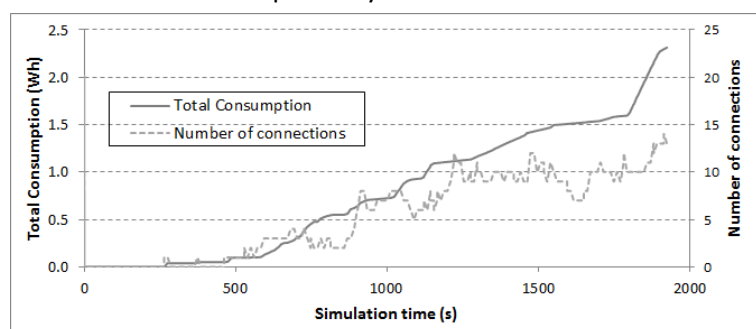


Figure 139: Total energy consumption of the BS with 30 terminals

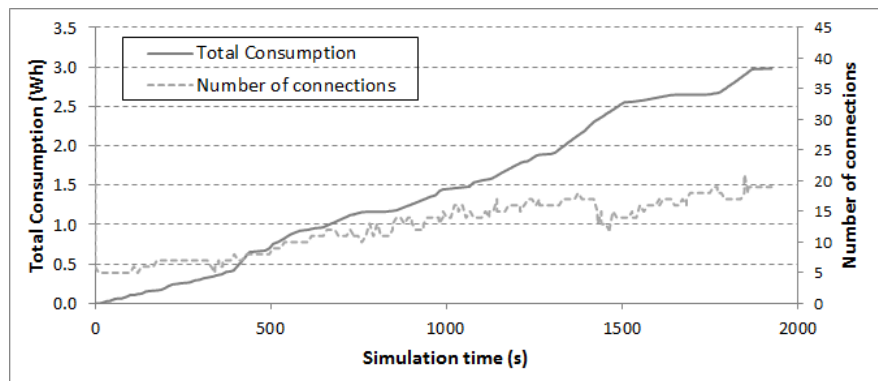


Figure 140: Total energy consumption of the BS with 40 terminals

Finally, Figure 141 illustrates a comparison of the total energy consumption of the BS for the aforementioned cases. More specifically, for the case of the network with 30 terminals, the consumption of the BS was 2.71 Wh. When 10 more terminals were added to the network, the BS consumption increased by 10% and reached 3.01 Wh. Finally, when terminals increased to 50 the BS consumption increased by 15% in comparison with the case of 40 terminals. As a result, as it was expected the energy consumption of the BS tends to increase when the number of terminals also increases.

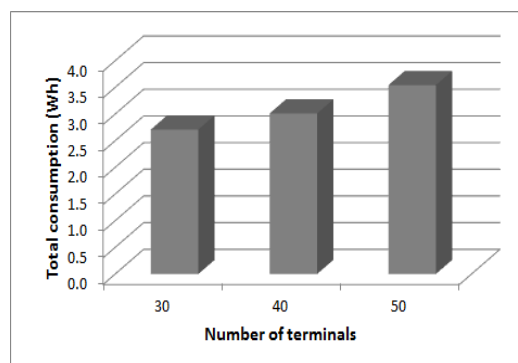


Figure 141: Total energy consumption of the BS for a network with 30, 40 and 50 terminals

Test case 3

In this test case, the battery consumption of terminals will be examined. More specifically a terminal that is served exclusively through the macro BS (macro User Equipment (UE)), a terminal that is served only through a femtocell (femto UE) and a terminal that is moving and can be served from the BS and a femtocell (UE), but not simultaneously will be studied.

Figure 142 depicts the progress of the energy level of a macro UE vs. the progress of the energy level of a femto UE vs. the progress of the energy level of a UE. It is assumed that the energy of a terminal decreases as time progresses and that also decreases when data are transmitted. In addition, it is assumed that the terminals send data every 30 secs. Apparently, the energy of the femto UE decreases at a lower rate since the terminal needs less transmission power to communicate with the femtocell, while the energy of the macro-terminal decreases in a high rate due to the high transmission power. On the other hand, the progress of the energy level of the moving terminal is in the middle of the progress of the femto-UE and the macro-UE as it was expected since when it is within the coverage of an available femtocell, i.e. in terms of capacity and accessibility, it connects to the femtocell, otherwise it connects to the BS. More specifically, as it can be observed in Figure 143, the battery lifetime, i.e. the time needed for the energy level of a terminal to reach 0, of a femto-UE is 19506, while for a macro UE the lifetime is 11400 and for the moving UE is 14263. Hence, the lifetime of a macro-UE is 41.56% lower than the one of a femto-UE and 25.12% lower than the one of the moving UE.

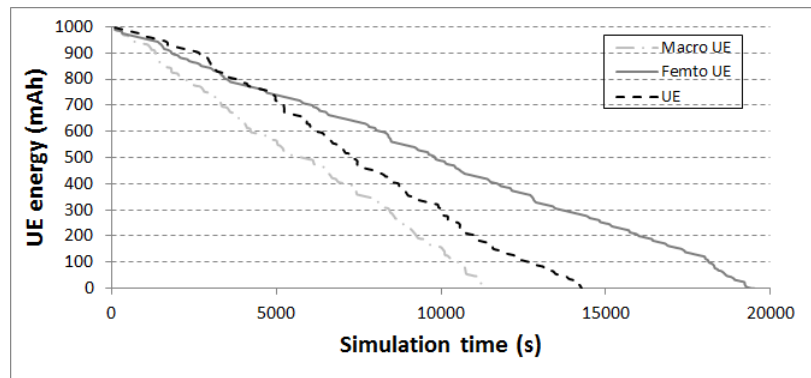


Figure 142: Progress of the energy level of macro-terminals, femto-terminals and terminals that connect both to macro BSs and femtocells

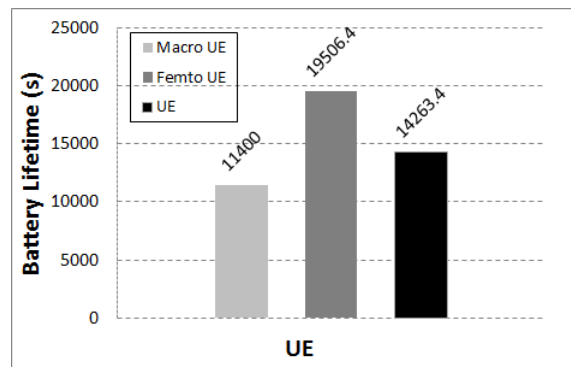


Figure 143: Battery lifetime of macro-terminals, femto-terminals and terminals that connect both to macro BSs and femtocells

3.16.3 Conclusions

This section aims at solving the complex optimization problem of allocation of network resources. The problem is mathematically formulated and solved by means of a novel greedy algorithm, namely the Dynamic Resource Allocation algorithm. Results from testing the proposed algorithm are presented and compared to those of the well-known Simulated Annealing and Tabu Search. Specifically, the DRA algorithm managed to outperform both the SA and TS algorithms in terms of solution quality and runtime. Regarding the quality of the solution, the DRA computed a solution that was 4.68% better than the one of the SA and 2.27% better than the one of the TS. As far as runtime is regarded, the DRA algorithm proved to be 36.68% faster than the SA and 2117.10% faster than the TS.

In addition, the benefits that derived from the use of femtocells at the energy consumption of a macro BS and the battery lifetime of terminals through 3 indicative test cases were studied. Simulation results depicted that the BS energy consumption is decreasing while the number of femtocells increases. The reason is that the more femtocells, the more traffic is acquired by the BS and therefore the number of terminals that connect to the BS is low. Moreover, it was illustrated that the BS energy consumption increases while the number of terminals increases in the network. The reason is that the more terminals in the network, the more connections will be made with the BS. As a result the BS needs higher transmission power to serve the terminals. Furthermore, the battery lifetime of a macro-terminal, a femto-terminal and a moving terminal was studied. Simulations illustrated that the battery lifetime of a femto-terminal is significantly higher than the one of the macro-terminal.

3.17 Support activity to validate ON algorithms on an offloading-oriented real-deployment testbed

3.17.1 Performance evaluation planning

3.17.1.1 Metrics to illustrate the performance

As described in section 2.16, the available simulator outputs after the ON simulation include a wide variety of radio KPIs that will allow a deep analysis of the performance of the ON mechanisms on this scenario. Some of these results are obtained in a map format, so a spatial analysis is required to assess the geographical impact of the tested algorithms. The remaining results are used to perform a statistical evaluation of the users' and femtos' situation under ON conditions.

The performance evaluation will then mainly include a benchmarking analysis of the results before and after the offloading, focusing on those indicators that allow to check if an enhancement has actually happened and measure its effects.

For example, the analysis of each test scenario would include evaluating indicators such as:

- *OneFIT Scenario 1 (Opportunistic Coverage Extension)*
 - Number of offloaded users
 - Number of overruled-CSG femtos
 - Number of disconnected users
 - Average and maximum UL transmission power in the extended coverage area
 - Load balance among macros surrounding the extended coverage area
 - Load balance among femtos inside the extended coverage area
 - Interference map inside the extended coverage area
- *OneFIT Scenario 2 (Opportunistic Capacity Extension)*
 - Number of offloaded users
 - Number of overruled-CSG femtos
 - Number of disconnected users
 - Average and maximum throughput in the hotspot area
 - Load balance among macros surrounding the hotspot area
 - Load balance among femtos inside the hotspot area
- *OneFIT Scenario 3 (Ad-hoc opportunistic network)*
 - Number of offloaded users
 - Number of overruled-CSG femtos
 - Number of users reaching or exceeding the target throughput
 - Average and maximum throughput in the service area
 - Load balance in the service area
 - Number of femtos reaching their maximum capacity

3.17.1.2 Benchmark references

The objective of this activity is to assess the performance of the OneFIT solution to offload traffic from the macro infrastructure towards the femto layer in certain situations. Therefore, a

benchmarking analysis is needed to compare the situation right after the offloading is completed to the scenario that triggered the ON establishment procedures. Such comparison will be done for each simulated test case to evaluate the ability of ON mechanisms to cope with different situations under the constraints of each scenario.

Additionally, a comprehensive comparison of the various test cases of each scenario will be carried out to check to what extent the ON offloading solution can be stressed. Examples of how these comparison analyses will be conducted are the following:

- OneFIT Scenario 1 is focused on the provision of service in areas where the infrastructure coverage is scarce, e.g. if a macro cell is suddenly disconnected. A benchmarking analysis can be done comparing the all-macros-on situation to scenarios where a single cell, then a complete site, then 2, 3 or 4 macros are disconnected.
- OneFIT Scenario 2 addresses an increase of the capacity of the infrastructure, e.g. when macro cells get congested. The benchmarking analysis will consist of several scenarios where the number of users connected to one or more of the macro cells is progressively increased.
- OneFIT Scenario 3 focuses on the provision of a specific service in a certain area, e.g. requiring a certain QoS or throughput level. In this case the benchmarking analysis will comprise different throughput requirements that should be fulfilled along with a progressive increase of the macro users.

3.17.1.3 Evaluation platform

In order to carry out this activity, two complementary simulation modules have been developed: an LTE system-level simulator and an ON engine:

LTE system level simulator:

The structure of the simulator is depicted in Figure 144.

The simulator comprises several submodules that feed the calculation kernel with different input information:

- Scenario configuration: includes features of the LTE scenario and sites (location, antenna parameters, transmission power, etc.)
- Radio environment: includes LTE operational parameters (bandwidth, power control...) and coverage calculations based on real 3D cartography and ray-tracing propagation models.
- Terminal characterization: includes information about UEs (capabilities, category...) and SINR vs. throughput curves obtained from simulations and field measurements.

The calculation kernel has been developed in C++ language and runs over a Linux workstation. It generates a number of output files that can be further analysed to evaluate the radio performance of the scenario. Some of these outputs include:

- Best server and main interferers identification
- SINR in DL and UL
- Throughput in DL and UL
- UL transmission power and UL/DL received power
- Disconnection causes
- Cell edge characterization
- RSRP (Reference Symbol Received Power), RSRQ (Reference Symbol Received Quality) and other radio KPIs.

Some of the outputs are raster map files that include the geographical features of the scenario and can be used to perform a spatial analysis of the network performance. The rest of the output files are tables with per node and per user aggregated results, histograms and statistic reports, etc.

The simulator is also able to work with different simultaneous infrastructure node layers (e.g. macro, micro and femto layers). In the case of femto nodes, a closed subscriber group (CSG) policy has to be set prior to the simulation. This policy controls whether a user is entitled to be connected to a certain femto node when it is detected as best server or is to be redirected to the nearest macro node.

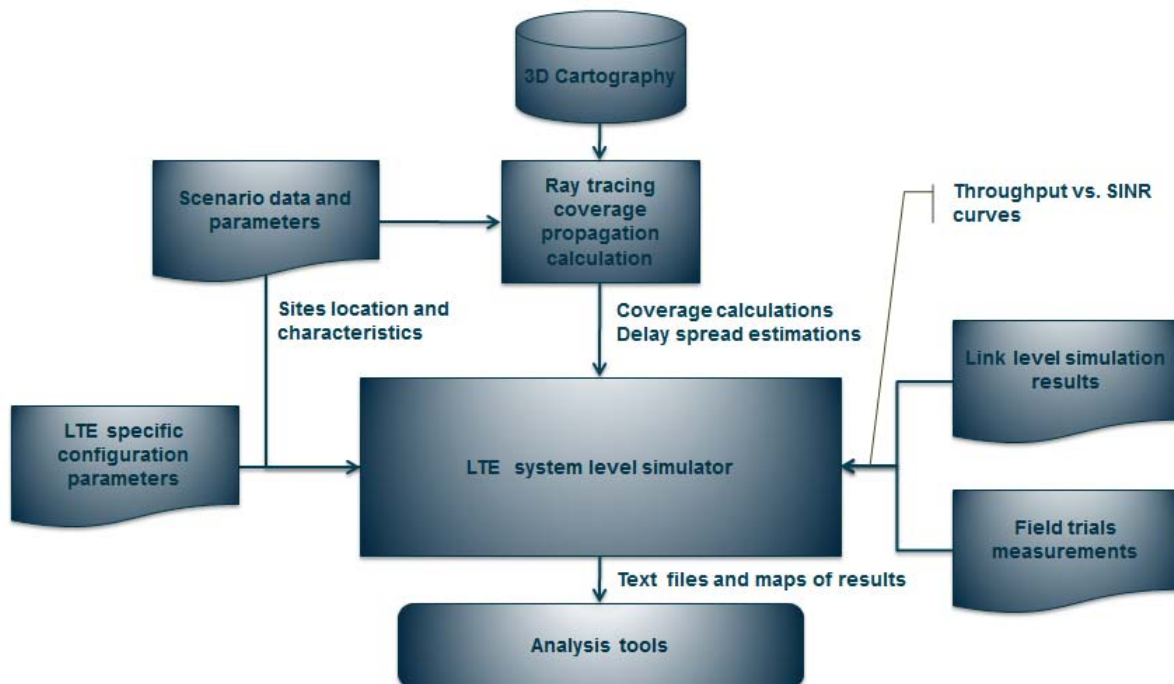


Figure 144: LTE Simulator structure

ON engine:

This module replicates the OneFIT mechanisms to simulate ON capabilities on the LTE network. The engine gathers the results from the simulator, processes them to add the opportunistic offloading functionalities and launches a new simulation process with the new topology.

The ON engine has been developed in Matlab language and runs on a Windows workstation. The communication with the LTE simulator is performed via configuration and results files.

This module's functionalities are those related with the OneFIT ON life cycle (namely suitability determination, node selection and topology reconfiguration) that enable the definition of an offloading mechanism (i.e. transferring part of the traffic coursed by the macro layer to the femto layer by creating an ON among the selected users and the surrounding femtos). To address this objective, as the transferred users do not belong to the femtos' CSGs, the ON must temporary overrule their policies. The complete simulated timeline would be the following:

- Cognitive mechanisms allow macros to become aware of the status of the surrounding femto layer (radio environment, traffic load...)
- Some situation (e.g. congestion, coverage gap, application provision) triggers the creation of an ON.
- Infrastructure establishes the ON among selected femtos and UEs (optionally, also with devices in femto's CSG).

- Data streams are handled through the femto layer instead of macro layer during the ON lifetime.
- A cognitive monitoring should be set to watch context changes and adapt the ON configuration to them.
- The infrastructure will revert to the initial status if the triggering situation ends or other circumstances arise. This rollback will include:
 - Femtos recover their original CSG policies.
 - Non-CSG UEs are diverted back to macro layer.
 - The ON is terminated.

3.17.2 Performance evaluation results

An initial test case has been designed to check the performance of the ON engine (see previous section). Over the base scenario described in section 2.16.1.2, about 1200 users have been randomly placed, as shown in the Figure 145, where red squares are users, blue dots are femto stations and green triangles are macro sites.

Inside the focus zone (the inner grey rectangle) there are 5 macro sites (15 macro cells), 126 femto stations and about 500 users. Most of the users (less than 400) are served by macro cells: more than 100 are disconnected due to low SINR levels, while the rest achieve a mean DL throughput of 0.9 Mb/s, as the cells are quite congested. On the other hand, femto users in the zone are more than 100 and only 11 are disconnected. The mean DL throughput for the remaining femto users is over 14 Mb/s.

For this scenario about 200 users (86 in the focus zone) have been identified as candidates to form Opportunistic Networks, namely those macro users that have a good SINR value from a neighbouring femto and thus, their traffic could be offloaded to the femto layer. To select which users would be finally part of the ONs, an objective function, based on equation (81), has been defined:

$$OF = \beta \left[\frac{1}{N_M + N_F} \sum_{j \in MUF} \sum_{j' \in MUF} \left(\alpha_j \frac{\varphi_j}{\varphi_{jMAX}} - \alpha_{j'} \frac{\varphi_{j'}}{\varphi_{j'MAX}} \right)^2 \right] + \delta \left[\frac{1}{N_U} \sum_{i \in U} \sum_{j \in MUF} d_{ij} \right] - \tau \left[\frac{1}{N_M + N_F} \sum_{j \in MUF} \varphi_j \right] \quad (94)$$

Where:

- β, δ, τ are the weights of the different blocks of the function (namely: load balance, distance to node and total throughput).
- N_M, N_F, N_U are the number of macro cells, femto stations and users, respectively.
- M, F, U are the sets of all the macro cells, all the femto stations and all the users, respectively.
- α are weights to adjust the contributions of femtos and macros to the load balance.
- φ_j and φ_{jMAX} are the total and the maximum achievable DL throughput of node j , respectively.
- d_{ij} is the distance from user i to node j .

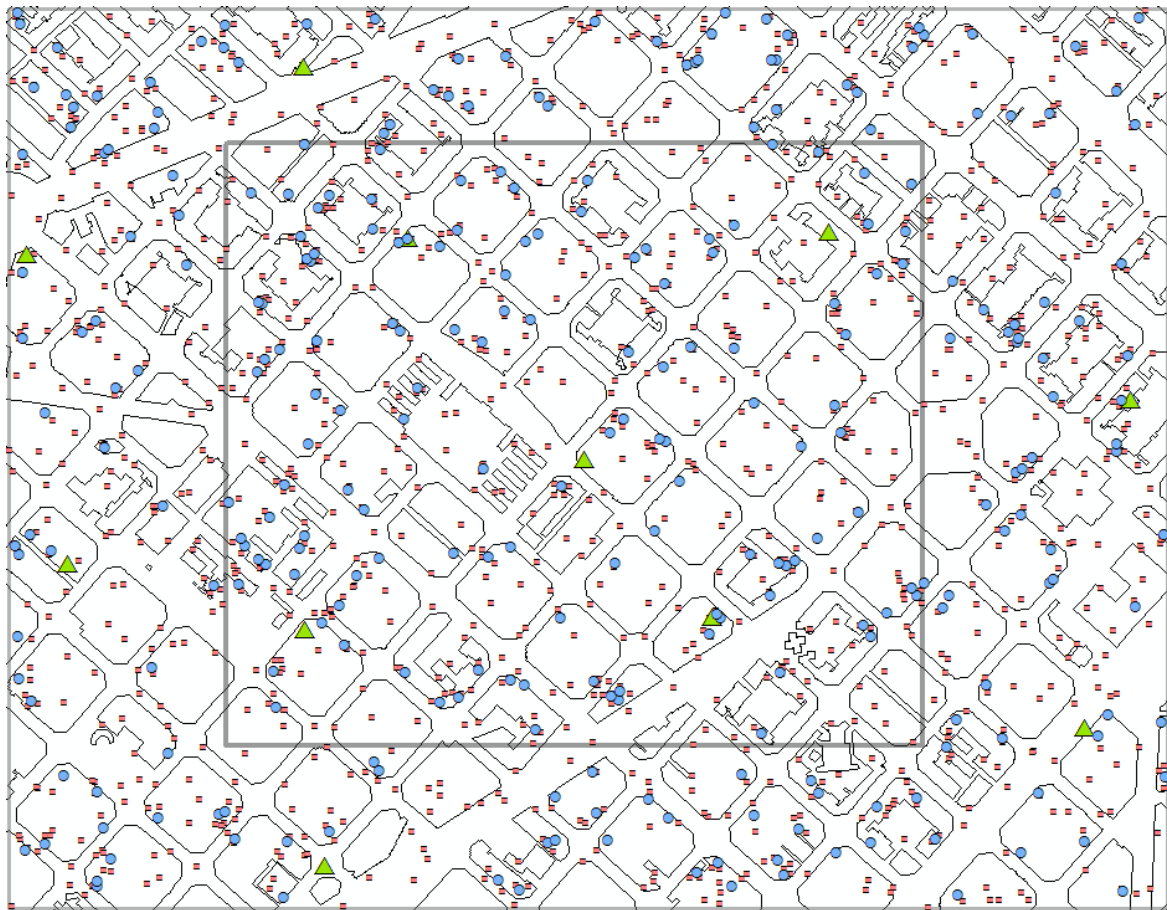


Figure 145: Initial scenario topology

This objective function should be minimised in order to reach a situation where a number of the candidate users have been offloaded to the femto layer in a way that users try to connect to the closest node, maximising the total throughput and optimising the load balance among nodes. To achieve the optimal value of the function, a genetic algorithm approach has been developed in Matlab.

In this initial test case, the optimisation of the objective function leads to a new situation in which 73 macro users of the focus zone have been offloaded towards neighbouring femtos. The offloading has extracted users from 21 macro cells and injected them into 64 femtos. This has caused a reduction of the disconnection rate and an increase of the mean DL throughput in macros. On the other hand, disconnection rate in femtos remains the same, but the throughput is reduced, as more users are sharing the limited resources of femto stations.

A histogram of the DL throughput values for the users inside the focus zone is shown in the next figure. The effect of macro users offloaded to the femto layer is observed as a reduction of the number of low-throughput macro users and as an increase of the number of shared femtos.

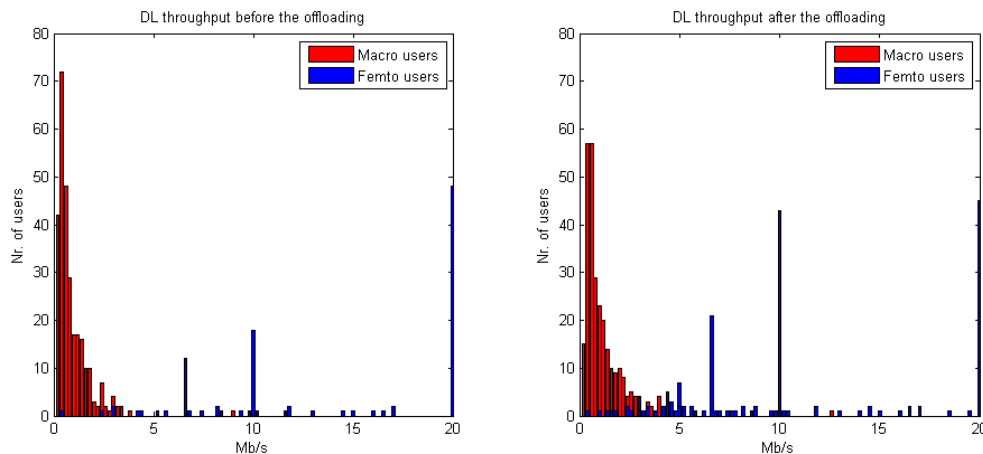


Figure 146: DL throughput

For those users that have been offloaded, an average DL throughput increase of 11.25 Mb/s is reported (being the minimum, 1 Mb/s, and the maximum, 20 Mb/s).

The following table summarises the results:

Table 11: Summary of algorithm performance

		Before the offloading	After the offloading
Macro	Nr. of users	389	316
	Nr. of disconnected users	103	33
	Mean DL throughput	0.9 Mb/s	1.2 Mb/s
	Total DL capacity	257 Mb/s	332 Mb/s
Femto	Nr. of users	115	188
	Nr. of disconnected users	11	11
	Mean DL throughput	14 Mb/s	11 Mb/s
	Total DL capacity	1460 Mb/s	1961 Mb/s
OF	Load balance value	110	99
	Overall OF value	193	128

3.17.3 Conclusions

This section has described the implementation of the evaluation platform that will be used to assess the performance of the OneFIT algorithms to develop a macro-to-femto offloading mechanism in urban areas.

The first tests on the platform show results that are coherent with the expected functionality. Tests prove that the offloading mechanism behaves properly, leading to a scenario with a 70% reduction in the disconnection rate, a 35% increase in the total capacity and a 10% enhancement in the load balance indicator.

Further work on this platform will be focused on the performance evaluation in several subcases of the OneFIT business scenarios, including some stress tests to assess the range of application of this mechanism.

4. Synergies and Integration

4.1 General approach and roadmap

This section presents the general approach that has been followed in OneFIT WP4 related with the synergies and integration of the different algorithms for enabling opportunistic networks. Firstly, subsection 4.1.1 presents the results of the first analysis that was carried out to identify the different interactions and synergies between the different technical activities of WP4. As a result of this analysis, two major blocks were identified, dealing with spectrum opportunity identification and selection and with node and route selection, respectively. Then, subsections 4.1.2 and 4.1.3 present the roadmap for the completion of the synergies and integration task. Specifically, the steps towards defining the comprehensive OneFIT solution for the two identified major blocks are discussed in 4.1.2 and the steps for the OneFIT solution for ON management are discussed in 4.1.3.

4.1.1 Initial analysis of interactions & synergies

Even though the official start of Task 4.3 “Algorithms for enabling opportunistic networks: synergies and integration” was in September 2011, the analysis of interactions&synergies among the different technical activities in WP4 was already initiated in July 2011. The first step taken was the identification of commonalities among the different activities in WP4 that were described in deliverable D4.1 [22]. This was done by classifying them based on the technical challenge that they are addressing, the ON management stage of the ON lifecycle that they consider, and the scenario they focus on. This exercise is shown in Figure 147.

As a result of the above exercise, the analysis continued by further exploring the dimension related to the technical challenge. In this respect, two major blocks were identified:

- Spectrum opportunity identification and selection (*main players: UPC, VTT, UNIS*):
 - Modular decision flow for selecting frequency, bandwidth and RAT
 - Fittingness-factor based spectrum selection
 - Machine Learning based knowledge acquisition on spectrum usage
 - Techniques for aggregation of available spectrum bands/fragments
- Route and node selection (*main players: UPRC, TCF, UNIS, NTUK, LCI*):
 - Knowledge based suitability determination
 - Selection of Nodes and Routes
 - Route pattern selection in ad-hoc network
 - QoS and Spectrum aware routing techniques
 - Multi-flow routes co-determination
 - Techniques for network reconfiguration-topology design
 - UE to UE Trusted paths
 - Application cognitive multipath routing in wireless mesh networks
 - Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

		Discovery of terminals supporting ONS	Modular decision flow for selecting frequency, bandwidth and RAT	Fittingness-factor based spectrum selection	Machine Learning based knowledge acq. On spectrum usage	Techniques for aggr. Of available spectrum bands/fragments	Knowledge based suitability determination	UE to UE Trusted paths	Selection of Nodes and Routes	Route pattern selection in ad-hoc network	QoS and Spectrum aware routing techniques	Application cognitive multipath routing in wireless mesh networks	Multi-flow routes co-determination	Techniques for network reconfiguration-topology design	Content conditioning and distributed storage virtualization
Technical challenge	Node discovery	X													
	Node selection						X		X						X
	Route selection						X	X	X	X	X	X	X	X	
	Spectrum identification		X	X	X										
ON Management stage	Spectrum selection		X	X	X	X					X				
	Suitability	X	X		X		X			X	X	X			X
	Creation	X	X	X	X	X		X	X		X	X	X	X	X
	Maintenance & Termination	X	X	X	X	X				X	X	X	X	X	X
Scenario	Scenario 1	X	X	X	X	X	X	X	X	X	X		X	X	
	Scenario 2	X	X	X	X	X			X	X	X		X	X	
	Scenario 3	X	X	X	X	X	X	X	X	X	X		X	X	
	Scenario 4	X	X	X	X	X	X	X	X					X	
	Scenario 5		X	X	X	X	X		X			X			X

Figure 147: Identification of commonalities among activities

Following this, a number of point-to-point discussions in the different groups to carry out the detailed analysis of the interactions and synergies were triggered. To this end, a leading partner per group was nominated: UPC for the spectrum topic and UPRC/LCI for the nodes&routes topic. The analysis targeted to identify the commonalities and specificities of the different approaches, and as a result to identify the potential synergies. The analysis, summarised in the next sub-chapters, tried to answer the following questions:

- What solution principles are common to the different approaches?
- What solution principles are different to the different approaches?
- Identify complementarities: Can the different solution principles be combined?
- Identify alternatives: Can the different solutions be compared?

4.1.1.1 Spectrum opportunity identification and selection

In the following the outcomes of the analysis of the interactions & synergies associated to the different tasks dealing with spectrum opportunity identification and selection is given. These tasks are:

- Task 1.- Modular decision flow based approach
- Task 2.- Fittingness factor based approach
- Task 3.- Machine Learning based knowledge acquisition on spectrum usage
- Task 4.- Techniques for aggregation of available spectrum bands/fragments

The analysis work identified first the following commonalities among the different tasks:

- Several input parameters are similar in all the solutions of the different tasks

- Statistics used (e.g. duration of on/off periods, duty cycle, etc.)
 - Application requirements and constraints (e.g. required bit rate, available transmit power, etc.)
- All solutions consider learning and historic information
- Solutions of tasks 2 and 4 make use of utility functions
- Solutions of tasks 2,3 and 4 consider spectrum HO

Similarly, the following specificities were found among the considered approaches:

- Task 2 considers second order statistics (e.g. correlation, similarity)
- Task 4 focuses on spectrum aggregation of disjoint bands
- Task 1 considers operator preferences and UE speed
- Task 1 includes the selection of the RAT jointly with the spectrum and bandwidth
- The decision-making solution in Task 2 adapts to dynamic radio conditions (e.g. changes in interference conditions, path loss)
- Task 1 solution includes the configuration of sensing using fuzzy logic

Based on the above elements, the potential synergies among the considered approaches were identified as:

- Consolidation of the importance of common input parameters
 - Statistics used in the spectrum opportunity identification (e.g. duration of on/off periods, duty cycle, etc.)
 - Application requirements and constraints (e.g. required bit rate, available transmit power, etc.)
- Consolidation of the importance of partner-specific input parameters
 - Operator preferences
 - UE speed
 - Second order statistics (e.g. correlation, similarity)
- Consolidation of the importance of the specificities in a spectrum opportunity identification and selection solution:
 - Use of utility functions
 - Spectrum aggregation of disjoint bands
 - Consideration of learning and historic information
 - Consideration of spectrum handover
 - Adaptability to dynamic radio conditions (e.g. changes in interference conditions, path loss) in the decision making process
 - Inclusion of the configuration of sensing using fuzzy logic in the spectrum opportunity identification & selection problem
 - Joint consideration of the RAT in the spectrum selection problem.

4.1.1.2 Nodes and routes selection

One of two main challenges associated with ON management is selection and selection of appropriate set of nodes and routes from which the ON will be created. Nine of the WP4 algorithms address this challenge. These algorithms cover different scenarios (use cases) and approach to the problem at hand in different ways. The proposed algorithms are building blocks of the CMON and CSCI management systems and can be utilized in specific situations or can be considered as a generic solution for all ON related challenges. Analysis of interaction and synergies between these WP4 algorithms is conducted in order to identify similarities and differences in definition of the algorithms. The outcomes of the analysis of the interactions & synergies associated to the different tasks dealing with route and node discovery and selection are given below. The tasks (algorithms) are:

- Task 1.- Knowledge-based suitability determination
- Task 2.- Selection of Nodes and Routes
- Task 3.- Route pattern selection in ad-hoc network
- Task 4.- QoS and Spectrum aware routing techniques
- Task 5.- Multi-flow routes co-determination
- Task 6.- Techniques for network reconfiguration-topology design
- Task 7.- UE to UE Trusted paths
- Task 8.- Application cognitive multipath routing in wireless mesh networks
- Task 9.- Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

The analysis work has identified the following commonalities among the different tasks:

- Solutions of tasks 2, 5 and 8 make use of traffic flows between terminals and/or infrastructure nodes
- Solutions of tasks 3, 4, 6, 7 and 9 make use of common node capabilities such as:
 - Supported RATs
 - Current and maximum power levels, energy consumption
 - Mobility (direction, speed)
 - WLAN/ON capabilities
 - Caching capabilities and status of the cache storage in nodes
- Solutions of tasks 1, 4 and 8 make use of common QoS metrics and routing protocols such as:
 - Delay
 - Data rate
 - Available bandwidth on a link
 - ETX
 - Routing protocols (e.g. AODV, OLSR, QOLSR)
- Solutions in tasks 3 and 8 consider user application classes. Identified classes are:
 - Conversational class (i.e. VoIP)
 - Streaming class (i.e. video streaming)

- Interactive class (i.e. video games)
- Background class

On the other hand, the following specificities have been found among the considered approaches:

- Task 7 considers the ciphering key as part of the proposed solution. For establishing a secure direct UE to UE path, the algorithm will have to determine the secure element, like the data link ciphering key.
- Task 5 focuses on network coding, Mtopo messages, memorization and pivot nodes. Regarding network coding, the proposed algorithm combines the (re)routing of traffic flows on ad-hoc network with a throughput optimization technique called network coding. This optimization technique proposes to use the common routing paths of multi-flows to reduce the information to transmit on these paths, benefiting by the information transmitted on other paths for these flows. Regarding Mtopo messages, these messages are sent periodically from candidate egress nodes which contain information on the flows.
- Task 4 considers spectrum aware routing which is based on utilizing a multi-layer model for routing protocols
- Task 6 takes into account topology control which will enable topology formation and control during ON creation, maintenance and termination phases.
- Task 1 considers the feasibility of creating an ON, prior to the creation of it.
- Task 2 focuses on the one hand on the problem of maximum flow (centralized approach of selection of nodes and routes) and on the other hand provides fitness values for the selection of the best nodes (distributed approach on the selection of nodes and routes).
- Task 8 deals with aggregation of backhaul bandwidth resources in WMNs only
- Task 9 deals with a problem of proactive and reactive multimedia content placement on WMN access points

Based on the above elements, the potential synergies among the considered approaches are identified as follows:

- The security features defined by Task 7 on the definition of “UE-to-UE Trusted Direct Path” algorithm focus on establishing a secure direct UE to UE path. The algorithm will have to determine the secure element, like the data link ciphering key. Security features like those proposed by Task 7 could be taken into consideration by other approaches as well.
- Also, traffic flows are considered by algorithms developed by Task 8, Task 5 and Task 2. Algorithm of Task 5 on “multi-flow routes co-determination” proposes to generalize the modification to be applied on existing established flows in order to optimize the flows in using the network coding flows optimization capabilities. Algorithm of Task 2 on “selection of nodes and routes” provides a centralized approach to the problem. Also, the Ford-Fulkerson’s algorithm on maximum flow is considered in order to determine flows of the ON. Task 8 takes into account the existing and reoccurring traffic patterns in backhaul of the WMNs in order to determine the most appropriate routes over which to provide the backhaul bandwidth aggregation. Moreover, common parameters are used in most of the proposed algorithms, so the comparison between various implementations would be possible.
- Procedures defined in Task 1 can be applied (more or less modified) on suitability determination phase of every of the remaining tasks.
- Tasks 3 and 8 can cooperate in order to emphasise the need for user application profile awareness in ad-hoc mode and access and backhaul side of the infrastructure mode.

- Coordination of Tasks 2 and 8 can provide opportunistic bandwidth aggregation and load balancing in both access and backhaul side of the operator's infrastructure.

In addition to the previous analysis, a particular focus has been placed on the different approaches for nodes and routes selections in use cases specific to the OneFIT scenario 5 (Opportunistic resource aggregation in the backhaul). These are covered in particular in Tasks 1,2, 8 and 9. The following conclusions have been obtained:

- What solution principles are common to the different approaches?
 - Common link data input
 - Task 8: Status of network links (available capacity of a link, channel used, interference levels, expected delay, packet drop - ETX...)
 - Task 1: Delay, data received (Kbps), data dropped (Kbps), throughput, jitter
 - Task 2: capacity of link, flow of link, link cost, link RAT
 - Operator policies consideration
 - Task 8: Operator policies (required resource utilization levels, required QoS levels for different applications and groups of users)
 - Task 1: Maximization of QoS, Minimization of energy consumption
 - Routing protocols
 - Task 1: e.g. AODV, OLSR, GRP
 - Task 8: e.g. OLSR
 - Centralized and distributed approaches of algorithms
 - Tasks 9 and 8: i) centralized approach –decision making on ON suitability, creation and maintenance to take place on a wireless controller/management server, ii) distributed approach – APs will run the algorithm and ON logic
 - Task 2: i) centralized approach –Based on Ford-Fulkerson maximum flow algorithm for the selection of paths for the ON creation and maintenance, ii) distributed approach – Determination of a fitness value for the selection of best nodes among a pool of candidate ones which will participate to the ON formation
- What solution principles are different to the different approaches?
 - Task 9:
 - Node selection to support content placement: node selection during ON suitability determination, creation and maintenance phases in order to support proactive and reactive caching mechanisms for video content delivery/streaming over pervasive wireless mesh networks (WMN)
 - Proactive and reactive content placement algorithms
 - ONs created among infrastructure nodes (APs) only – Node discovery procedure is not needed because these nodes belong to the operator and their static characteristics (e.g. supported RATs, channels, number of interfaces, total storage capacity...) and capabilities (ON support, streaming capability...) are known in advance to the operator
 - Specific application – video delivery/streaming
 - Task 8:

- Multipath routing engine: Aggregation of available bandwidth in backhaul side of the infrastructure network. Creation of backhaul bandwidth pools which are monitored and utilized when and where needed (if available). Suitability determination phase takes into account profile of user's applications at access side of the network, utilization of available backhaul links, QoS achievable over network links and possibilities for creation of additional paths for providing backhaul bandwidth aggregation.
- ONs created among infrastructure nodes
- Specific network technology considered – WMN
- Task 1:
 - Make decisions upon the feasibility of creating an ON, prior to the creation of it, when judged as appropriate
 - Context-matching enhancement: In order to fulfil the requirement for more proactive and faster response to changes
- Task 2:
 - Centralized approach: Based on Ford-Fulkerson maximum flow algorithm
 - Distributed approach: Determination of a fitness value for the selection of best nodes among a pool of candidate ones
- Identify complementarities: Can the different solution principles be combined?
 - Tasks 8 and 9 focus on the management of resources on the backhaul side of the network, while Tasks 1 and 2 investigate and elaborate more on the wireless access. The definition of a common framework for the backhaul and the wireless access ON algorithms could create synergies to be further explored in the different tasks. Moreover, task 9 considers in the "content conditioning and distributed storage virtualization/ aggregation for context driven media delivery" algorithm both centralized and distributed approaches in order to support content placement algorithms for video delivery/ streaming over pervasive wireless mesh networks (WMNs). Also Task 2 proposes centralized and distributed approaches for the "selection of nodes and routes" in order to determine eligible nodes for the creation of an ON. In all cases, the decision making of the centralized approaches relies on a central management entity/ controller. The logic of these central entities could be combined in order to elaborate on the concept of centralized management entities. Also, regarding the distributed approaches that are proposed, basic principles could be combined in order to elaborate on the logic and mechanisms for the handling of standalone opportunistic terminals. Additionally, the derivation of status of network links as proposed in the "application cognitive multi-path routing in wireless mesh networks" takes into account attributes that could pose similarities towards the solution proposed in task 2 on the "selection of nodes and routes". As a result, a combination could be possible.
- Identify alternatives: Can the different solutions be compared?
 - The main focus of the algorithms of tasks 8 and 9 is the management of resources on the backhaul side of the network (specifically WMN networks), while tasks 1 and 2 investigate and elaborate more on the wireless access. The derivation of results from both studies could be compared in order to define a common framework for the solution of problems in both the backhaul and the wireless access. Backhaul and access resource management should benefit from cooperation of the proposed algorithms in order to achieve better system performance, resource utilization and QoS.

Route and node identification and selection procedures in Tasks 2 and 8 can be combined in order to provide an overall backhaul bandwidth aggregation in operator's network. This overall backhaul bandwidth aggregation is analyzed in case of the wireless mesh networks. The used techniques are:

- Task 2 – Opportunistic capacity extension in the access side of the WMN through neighbouring terminals
- Task 8 – Algorithm for opportunistic backhaul bandwidth aggregation in WMN

The biggest challenge facing multi-hop wireless networks today is poor bandwidth utilization, resulting with decrease in capacity of the overall network. This poor bandwidth resource utilization is effect of the access to the shared medium, common gateway related problems (few GWs for many wireless nodes) and interferences (intra and inter-flow) on multi-hop wireless transmissions. These effects induce problems in both access and backhaul communication within WMNs. With an intelligent and context aware backhaul bandwidth management schema, WMNs should be able to provide increased network access capacity in wider area, without the need for installation of additional GWs.

A properly constructed WMN requires that every node in the topology can connect to at least two other nodes in order to provide fault tolerance. Also, good engineering practice is to construct a topology which will provide paths to more than one GW for every AP. Such topologies provide great path diversity for the wireless backbone of WMNs. This diversity forms a solid ground for specific load balancing and multi-path routing schemes. Also, it is a good engineering practice to provide a certain level of overlapping between access coverage areas of WMN APs. This is necessary in order to enable high performance handover for modern mobile users within the WMN. This can result in situations where one end user is in the coverage area of two or more WMN APs, which provides opportunities for forced handover of users among WMN APs in order to achieve better load balancing. By gathering and analyzing contextual data, relevant for the backhaul and access links' operations, we are able to understand behavioral patterns of the system and to detect problems in backhaul and access side of the WMN before they become acute. These behavioral patterns will act as triggers for opportunistic backhaul and access bandwidth aggregation.

The ONs are created in order to exploit opportunities of the radio environment that appear in a specific place and time. For example, in the bandwidth aggregation scenario, a WMN AP, which experiences congestion, resulting in decreased QoS (Quality of Service), could redirect a portion of the users that are closely located (e.g. in a range of a typical Wi-Fi connection) into an alternate WMN AP. As a result, the users will enjoy better quality of the requested service. Also, aspects of the bandwidth aggregation could be implemented in backhaul segments of the WMN in order to provide mechanisms for sharing and assignment of bandwidth resources wherever and whenever needed in an opportunistic manner. The creation of different ONs, in order to provide necessary bandwidth aggregation at access and backhaul side of the WMN, is shown in Figure 148.

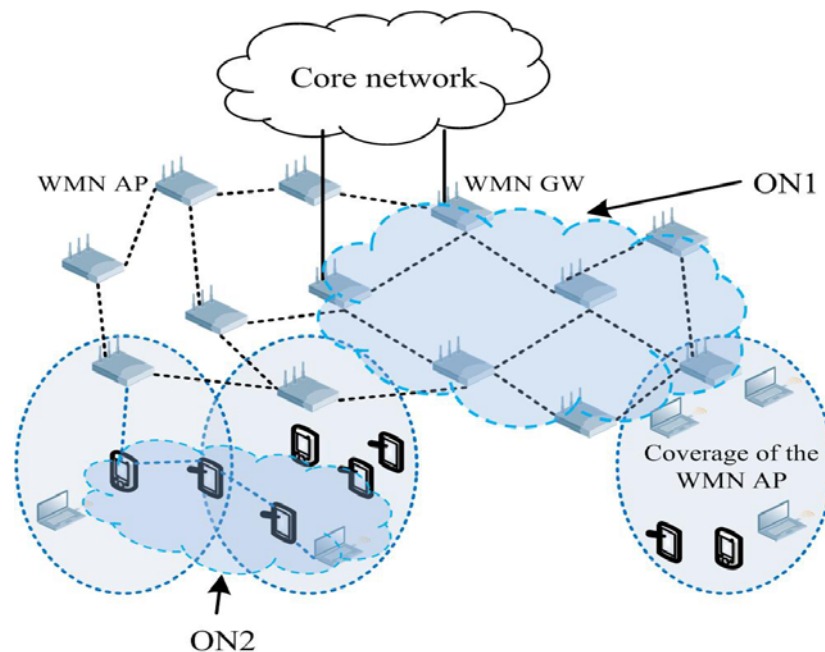


Figure 148: ONs for providing bandwidth management in the backhaul (ON1) and access (ON2) side of the WMN

Bandwidth aggregation in the backhaul of the WMN will be provided through means of multi-path routing (Task 8). If the backhaul bandwidth aggregation scheme is not feasible, then struggling AP can be provided with necessary additional bandwidth from available access capacity of non-congested WMN APs. Specifically, given the set of congested APs, the set of terminals that will be moved from the congested area and the set of non-congested APs that can help in the situation handling, find the paths for redirecting application flows from terminals in congested APs to alternate APs (approach in line with Task 2).

By monitoring of WMN resources, the current load balancing and inspection of the history of contextual changes, a need for bandwidth aggregation can be detected. This detection is a trigger for ON suitability determination phase. This phase relies heavily on context awareness and previously built knowledge database in order to provide fast and appropriate decision making. As part of the suitability determination phase, WMN management system will decide how to address the problem at hand. First, it will check whether or not the detected problem can be solved with aggregation of WMN backhaul bandwidth through selection of multiple paths from available GWs to the struggling APs. If the problem cannot be solved with this approach, then possibilities for aggregation of the available access bandwidth of neighboring APs will be checked. These two bandwidth aggregation approaches are not mutually exclusive. On the contrary, in order to provide the highest level of available bandwidth utilization, these two solutions need to be deployed at the same time.

Moreover, a solution that derives from Task 2 (selection of nodes and routes) could involve the utilization of femtocells in order to provide capacity extension/offloading. To that respect, synergic operations are possible between the support activity to validate ON algorithms on an offloading-oriented real-deployment testbed and the capacity extension through femtocells. Specifically, algorithmic techniques of Task 2 could complement the support activity to validate ON algorithms on an offloading-oriented approach as both approaches shall consider algorithms that redirect traffic from macrocells (usually congested with poor communication quality) into an opportunistic set of small-sized cells/ femtocells for coverage, capacity or quality enhancement purposes.

4.1.2 Comprehensive OneFIT solution for spectrum and nodes&routes

Based on the analysis for the group on the spectrum topic and the group on the nodes&routes topic, the first goal was to develop these synergies based on point-to-point discussion among the considered partners making use of the simulations results obtained from each partner's activity. The objective is the specification of a comprehensive solution framework for spectrum selection in ONs (similarly, for the nodes&routes selection) jointly considering the different tasks in a holistic way. Ad-hoc simulations to support specific aspects towards the definition of the comprehensive solution will be run when suitable. Close cooperation and discussion among the involved partners is envisaged at this stage.

The specific plan was the following:

- Formulation of the solution framework for a comprehensive OneFIT solution for the spectrum selection topic by February 2012.
- Formulation of the solution framework for a comprehensive OneFIT solution for the nodes&routes selection topic by February 2012.
- Comprehensive OneFIT solution for the spectrum selection topic supported by simulation results by June 2012.
- Comprehensive OneFIT solution for the nodes&routes selection topic supported by simulation results by June 2012.

4.1.3 Comprehensive OneFIT solution for ON management

From July 2012 to December 2012, WP4 work will be associated to Task 4.3 and will take D4.2 as initial reference point. The work during this period will target (1) the definition of the final version of the algorithmic solutions forenabling ONs, with further results validating the algorithms and (2) the definition of a comprehensive solution, as a result of the functional integration and synergic operation among the different algorithms, and the description of the overall dynamic operation of the ONs, together with the evaluation of the integrated algorithms for selected cases.

4.2 Comprehensive OneFIT solution for spectrum opportunity identification and selection

4.2.1 Description of the solution

The general cognitive management solution for spectrum selection considered in OneFIT is shown in Figure 149. It is based on the interaction between a decision making entity and a knowledge management functional block. Both elements are residing in the infrastructure of the operator that is governing the ONs. The different sections where the components of the different blocks are elaborated are indicated in the figure.

The knowledge management functional block includes on the one hand the current knowledge on spectrum use indicating the status (e.g. idle/busy) of the available spectrum portions as well as different features of each portion (e.g. measured noise and interference, etc.). This information can be processed and stored in a database in the form of different statistics reflecting the experience of past situations. Such database can be used by learning methods to support the decision making processes.

The decision making entity contains two main elements. The first one is the spectrum selection, that decides which spectrum portion is to be assigned to each communication link in the network. The spectrum selection strategy is based on an objective function such as the fittingness factor and it can include spectrum aggregation capabilities as well as it can integrate the RAT selection together with the spectrum selection. In turn, the decision on the method to obtain knowledge on spectrum use

will select the most adequate strategy and configuration for acquiring knowledge about the status of the different spectrum portions (e.g. sensing method, control channel, etc.).

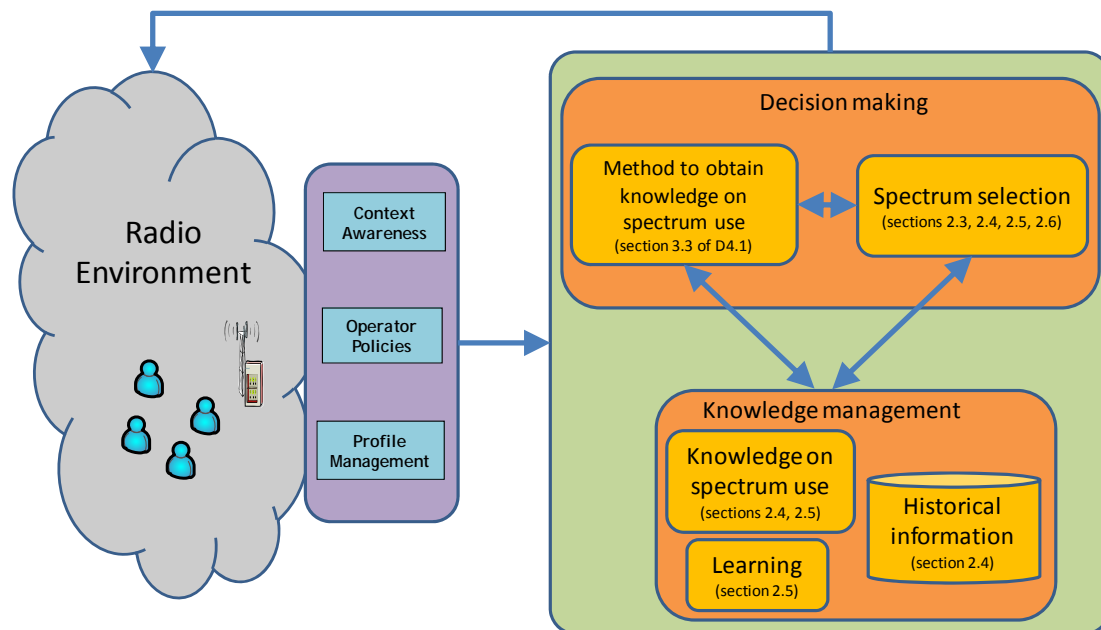


Figure 149: General framework for spectrum selection

Both decision making and knowledge management blocks use the information captured from the radio environment where the network operates. This information is categorized in terms of context awareness, operator policies and user/application profiles, as detailed in the following:

- **Policy related information:** This information contains knowledge about frequency bands that are permitted to be used for ON purposes, transmission power constraints in each band, and allowed bandwidths. Policies may indicate also the method to obtain knowledge on spectrum use in specific bands and, in case of sensing, they can define different sensing parameters such as probability of detection, sensing threshold, and minimum time required for spectrum sensing.
- **Profile related parameters:** Each mobile device involved with ON creation needs to exchange information about its own parameters and capabilities. This includes device capabilities such as spectrum aggregation capability, spectrum sensing capabilities, and network interface capabilities (e.g. supported bit rates and bandwidths of each network interface). This category also includes information about the application requirements such as minimum bit rate, latency, application duration, etc. used to guarantee Quality of Service (QoS) for different applications. Finally, other aspects such as terminal location or terminal speed are also considered.
- **Context awareness information:** This refers to information about how the spectrum is used in the different bands, including spectrum occupancy for the specific time/place where the ON operates. The available spectrum is organized in pools characterized by their central frequencies and bandwidths. This category of inputs also includes the measurements to monitor the degree of QoS of the applications in the ON, in terms of the actual bit rate that is achieved by a given link in the assigned pool.

4.2.2 Performance evaluation

This section intends to provide an evaluation of the different elements of the spectrum selection framework with the main target to consolidate the importance of the different specificities in the different solution. For that purpose, the following sub-sections intend to demonstrate, by means of results, the relevance of each one of the ingredients in the proposed framework.

4.2.2.1 Benefits of using utility functions

The framework for spectrum selection in OneFIT relies on the use of some type of utility functions that capture on the one hand the degree of fulfilment of the different requirements associated to the applications that use the different ON links and, on the other hand, the adequacy of these requirements to the available bit rates in each spectrum portion related to the propagation and interference conditions. In the following, a set of results are presented to reflect the benefit that utility functions introduce into the problem, taking as a reference the fittingness factor function defined in section 2.4. In that respect, two different fittingness factor functions are compared:

- Function $1f_1(U_{l,p})$: This fittingness factor is the utility function $U_{l,p}$ defined in equation (2) (see section 2.4.2) that is a monotonically increasing function of the available bit rate $R(l,p)$ for the link l in pool p in relation to the required bit rate $R_{req,l}$ by link l .
- Function $2f_2(U_{l,p})$: This is the fittingness factor proposed in section 2.4.2. It increases with $R(l,p)$ up to the maximum at $R(l,p) = \sqrt[\xi]{\xi - 1} \times R_{req,l}$ and then it decreases for $R(l,p) >> R_{req,l}$ which targets an efficient usage of spectral resources by reducing the value of the fittingness factor whenever the available bit rate is much higher than the required one.

To analyse the relevance of these functions, the following simulations consider a scenario with two types of radio links where the l -th link generates sessions with arrival rate λ_l and constant session duration $T_{req,l}$. Link #1 is associated to low-data-rate sessions ($R_{req,1}=64\text{Kbps}$, $T_{req,1}=2\text{min}$) while link #2 is associated to high-data-rate sessions ($R_{req,2}=1\text{Mbps}$, $T_{req,2}=20\text{min}$). The total offered load $\lambda_1 \cdot T_{req,1} \cdot R_{req,1} + \lambda_2 \cdot T_{req,2} \cdot R_{req,2}$ is varied in the different simulations. A total of 4 spectrum pools are considered where the total noise and interference power spectral density I_p experienced in each pool $p \in \{1..P\}$ follows a two-state discrete time Markov chain jumping between a state of low interference $I_0(p)$ and a state of high interference $I_1(p)$. Pools #1 and #2 are always in state $I_0(p)$ while pools #3 and #4 alternate between $I_0(p)$ and $I_1(p)$ randomly with transition probabilities for pool #3 $P_{10}=55.5 \cdot 10^{-5}$ (i.e. probability of moving from state I_1 to I_0 in a simulation step of 1s) and $P_{01}=3.7 \cdot 10^{-5}$ (i.e. probability of moving from state I_0 to I_1) and for pool #4 $P_{10}=8.33 \cdot 10^{-3}$, $P_{01}=55.5 \cdot 10^{-5}$. Based on these probabilities, the average duration of the high interference state is 30 min for pool #3 and 2 min for pool #4 while the average duration of the low interference state is 7.5h for pool #3 and 0.5h for pool #4. The achievable bit-rate in pools 1 and 2 is $R(l,1)=R(l,2)=128\text{ Kbps}$, while for pools 3 and 4, it alternates between $R(l,3)=R(l,4)=1536\text{ Kbps}$ for the $I_0(p)$ state, and $R(l,3)=R(l,4)=96\text{ Kbps}$ for the $I_1(p)$ state.

In order to isolate the effects of the spectrum selection executed at link establishment from the Spectrum Mobility, which will be analysed in a subsequent section 4.2.2.4.1, simulations just consider a Spectrum Selection strategy using the Knowledge Management block, and will be denoted in the following as SS+KM. Both spectrum selection and knowledge management algorithms are detailed in section 2.4.2. As a reference scheme for comparison in which no utility function is used, simulations consider a random selection strategy (*Rand*) in which a spectrum pool among the available ones is randomly selected without taking into consideration the adequacy of each pool to the requirements set by each link.

Figure 65 plots the dissatisfaction probability of link #2 (i.e. the most demanding in terms of required bit rate) as a function of the total offered traffic load $\lambda_1 \cdot T_{req,1} \cdot R_{req,1} + \lambda_2 \cdot T_{req,2} \cdot R_{req,2}$. It is defined as the probability of observing a bit rate below the service requirement $R_{req,l}$. Results for link #1 are not presented since its bit rate is always above the requirement of 64Kbps and thus it is all the time satisfied. As an additional result, Figure 151 plots the fraction of time that link #2 uses pools #3 or #4. When using these pools in the low interference state, link #2 will be satisfied. On the contrary, it will be dissatisfied whenever it is allocated pools #1 or #2 or pools #3 or #4 in the high interference state. As seen in Figure 65, for low traffic loads below 0.6Mbps, a very important reduction of the dissatisfaction probability compared to the reference scheme *Rand* not making use of utility functions is observed for both $f_1(U_{l,p})$ and $f_2(U_{l,p})$. This is because the KM component allows a proper

exploration of the different pools to identify the changes in their interference conditions and the utility function is able to adequately reflect which pool is more adequate to each link. Therefore, the most suitable pools are allocated to the different applications and, as a result, the dissatisfaction probability improves. The similar performance of $f_1(U_{l,p})$ and $f_2(U_{l,p})$ can be justified by the fact that, for this low traffic load, either pool #3 or #4 uses to be available for link #2, even if function $f_1(U_{l,p})$ tends to allocate these pools to link #1. This is reflected in Figure 151, where it can be seen that the usage of pools #3 or #4 by link #2 (when it is active) is close to 1 for both fittingness factor functions.

When load increases above 0.6 Mbps, performance degrades more significantly for $f_1(U_{l,p})$ than for $f_2(U_{l,p})$. This is because $f_1(U_{l,p})$ tends to allocate pools #3 and #4 to link #1 sessions, which forces link #2 sessions to use pools #1 and #2 that are not able to provide the required bit rate. On the contrary, $f_2(U_{l,p})$ prioritizes pools #1 and #2 for link #1 sessions and thus they tend to be available for link #2 usage, resulting in a much lower dissatisfaction probability. To illustrate the different allocation made by the two functions, it can be observed in Figure 151 that the usage of pools #3 or #4 by the most demanding link #2 is much higher with $f_2(U_{l,p})$ than with $f_1(U_{l,p})$. Note also in Figure 65 the significant reduction in dissatisfaction probability achieved thanks to the use of $f_2(U_{l,p})$ with respect to the *Rand* reference scheme which reflects the relevance of using utility functions in the spectrum selection process of the considered solution.

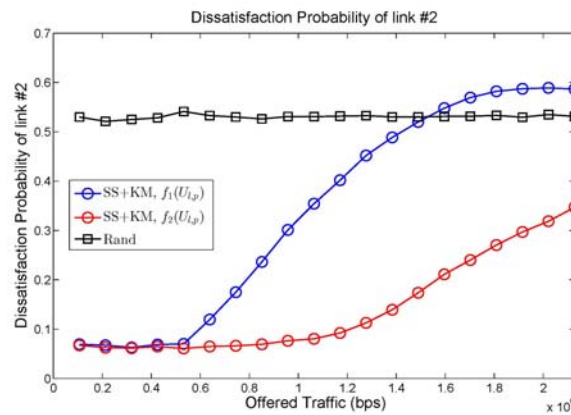


Figure 150: Dissatisfaction probability for the considered strategies

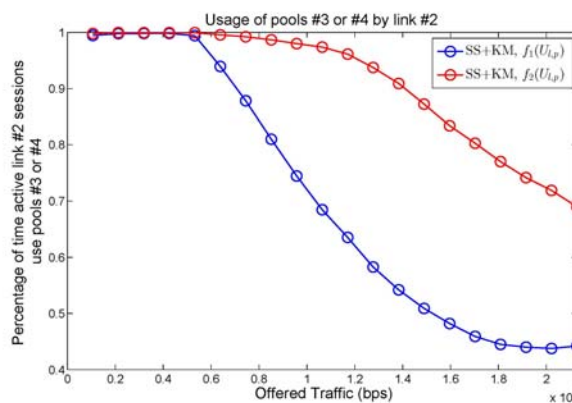


Figure 151: Fraction of usage of pools #3 or #4 by link #2

4.2.2.2 Benefits of applying knowledge management to historic information

In the following some results are presented to illustrate the importance of the Knowledge Management in the framework shown in Figure 149. This entity extracts the relevant information for the decision making based on the historical information regarding previous use of the different spectrum pools. For this purpose, the following schemes are analysed:

- Spectrum Selection only (SS): This is the proposed fittingness factor-based spectrum selection without the support of the Knowledge Manager (i.e. using only the last measured value of the fittingness factor) and without spectrum handover support.
- Spectrum selection supported by Knowledge Manager (SS+KM): This is the proposed fittingness factor-based spectrum selection supported by the Knowledge Manager block (using the algorithm in section 2.4.2.4) and without spectrum handover support.

The simulation conditions are the same as previously considered in section 3.5.2, with 2 types of links associated to two different requirements. Link #1 corresponds to low-data-rate sessions ($R_{req,1}=64Kbps$, $T_{req,1}=2min$) and link #2 to high-data-rate sessions ($R_{req,2}=1Mbps$, $T_{req,2}=20min$). Similarly, 4 spectrum pools are considered. The achievable bit rate in pools 1 and 2 is $R(l,1)=R(l,2)=512 Kbps$, while for pools 3 and 4, it alternates between $R(l,3)=R(l,4)=1536 Kbps$ for the low interference state $state_{l_0}(p)$, and $R(l,3)=R(l,4)=96Kbps$ for the high interference state $state_{l_1}(p)$. The average duration of the high interference state is 0.5h for pool #3 and 3h for pool #4 while the average duration of the low interference state is 7.5h for pool #3 and 21h for pool #4.

Figure 152 and Figure 153 plot, respectively, the total dissatisfaction probability as a function of the total offered traffic, and the fraction of time that either pool #3 or #4 are allocated to link#2 (note that link #2 will be satisfied only when using these pools in the low interference state, while it will be dissatisfied whenever it is allocated pools #1 or #2 or pools #3 or #4 during high interference states) is allocated to Notice that since link #1 is always satisfied regardless of the assigned pool (i.e., the bit-rate of link #1 is always above the requirement of 64Kbps), the total dissatisfaction probability depends only on link #2.

As seen in Figure 152, when comparing SS against SS+KM, for low traffic loads below 0.6Mbps the introduction of KM leads to a very important reduction of the dissatisfaction probability. The reason is that, whenever interference increases in pools #3 and #4 (i.e. they move to state l_1), the corresponding measured value of the fittingness factor $F_{l,p}$ will be LOW. As a result, the strategy SS that just keeps this last measured value of $F_{l,p}$ will decide in the future to allocate only pools #1 and #2, which offer a lower bit-rate. Then, the network will not be able to realize the situation when pools #3 and #4 move again to the low-interference state l_0 and become adequate for the link #2 (see in Figure 153 that the fraction of time that these pools are allocated to link #2 is close to 0). On the contrary, the use of the KM component considers the temporal properties of the $F_{l,p}$ statistics to disregard the last measured value and use an estimated value instead whenever a certain amount of time has elapsed since this last measure was taken. Correspondingly, sometime after the interference increase, the network will allocate again pools #3 and #4 to link #2, thus being able to identify if they have re-entered in the low-interference state. Note in Figure 153 that the fraction of time that link #2 uses pools #3 or #4 is close to 1 for the strategy making use of KM thus resulting in a better dissatisfaction probability. In summary, for low loads, KM allows a better exploration of the different pools to identify the changes in their interference conditions, and as a result the dissatisfaction probability improves. In turn, when load increases above 0.6 Mbps, pools #1 and #2 will tend to be occupied by link #1 sessions most of the time, which forces the system to assign pools #3 and #4 to link #2 sessions even with reduced $F_{l,p}$. In this case, interference reductions in pools #3 and #4 are detected without the use of KM. This is reflected in both Figure 152 and Figure 153 where, for high loads, the performances of SS and SS+KM are equivalent.

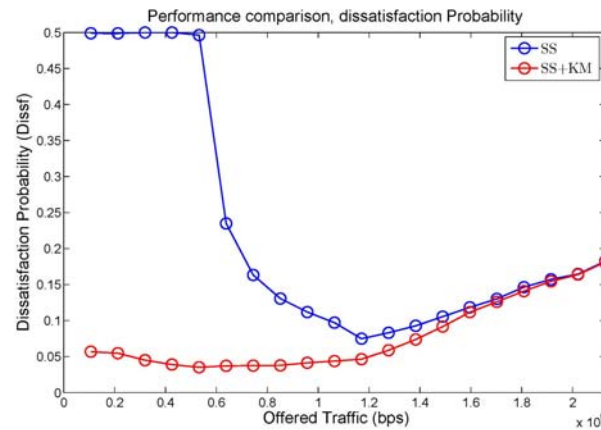


Figure 152: Effect of KM in terms of dissatisfaction probability

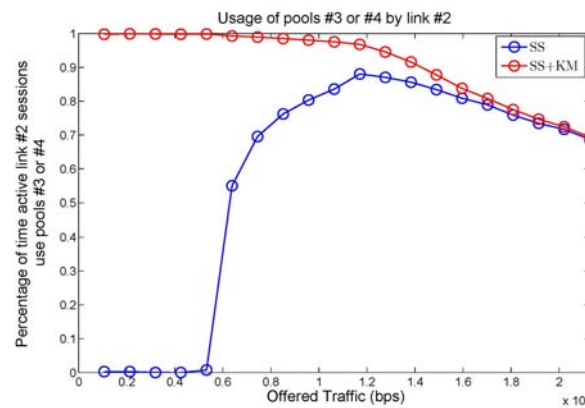


Figure 153: Effect of KM in terms of fraction of usage of pools #3 or #4 by link #2

4.2.2.3 Benefits of applying learning mechanisms

Machine-learning mechanism is adopted by the proposed utility-based spectrum aggregation and allocation algorithm which considers the complexity of spectrum aggregation as well as the channel switching and the total achievable throughput as explained in section 2.6. Those three objectives are integrated into a weighted sum utility function and the learning mechanism is utilized to decide the optimal weights setting which can depend on the (possibly periodic) variations in metric of interest. In the scenario that the system has pre-defined thresholds for each performance metric based on system level Key Performance Metrics (KPIs), the spectrum aggregation and allocation algorithm aims to maintain the performance of each objective remain close as possible to the pre-defined thresholds. When system detects the degradations in any of the performance metrics, the learning process is triggered to find the optimal weights setting depending on the situation. The reason of degradation of the performance metrics could be the radio environmental changes such as the primary users' activity pattern's change as well as changes in the pre-defined thresholds. The weights setting obtained as the result of the learning are applied to the utility function of the spectrum aggregation and allocation algorithm. In Figure 13 it is shown that by including a learning module, the proposed spectrum aggregation and allocation algorithm allows for the automated (versus manual setting) management of complex interactions and trade-offs between different metrics (without manual intervention) while the weight setting is adaptable and is modified depending on the application/environmental conditions encountered.

4.2.2.4 Benefits of providing adaptability to algorithmic solutions

This section presents some results to illustrate the importance of having algorithmic solutions in the decision making process with the capability to adapt to dynamic radio and contextual conditions (e.g. changes in interference conditions, path loss, etc.).

4.2.2.4.1 Adaptability provided by spectrum Handover

To assess the relevance of including spectrum mobility considerations that enable the change of assigned spectrum whenever variations in the context arise, let compare the following two schemes:

- Spectrum selection supported by Knowledge Manager (SS+KM): This is the proposed fittingness factor-based spectrum selection supported by the Knowledge Manager block (using the algorithm in section 2.4.2.4) and without spectrum handover support.
- Spectrum selection supported by both Knowledge Manager and spectrum mobility (SS+KM+SM): This is the proposed complete fittingness factor-based spectrum selection solution proposed in section 2.4.2 supported by both the Knowledge Manager block and the Spectrum Mobility (SM) algorithm that checks the convenience of executing spectrum handovers (SpHOs) either after variations in the interference of some spectrum pools or when a given link is released.

Simulation conditions are the same as previously discussed in section 4.2.2.2, with two types of links and four different pools available with different interference patterns.

Figure 154 plots the comparison in terms of dissatisfaction probability as a function of the offered load for the two considered strategies, while Figure 155 presents the fraction of time that either pool #3 or #4 is allocated to link #2, under the rationality that this link will be satisfied only when it is allocated one of these pools during the low interference state. With respect to the role of spectrum mobility, for low loads, its use leads to small improvements as seen in Figure 154. The reason is that, for low loads, it occurs very rarely that a link is not allocated to the pool with the highest fittingness factor because of being occupied by another link. Consequently, there is no need to perform SpHOs towards a better pool except in the case when the interference increases in the allocated pool, which justifies the small improvement observed when comparing SS+KM and SS+KM+SM. On the contrary, when load increases, it occurs more often that the preferred pool is occupied by another link and thus a pool offering lower bit-rate is allocated. In this case, the execution of SM after the release of the link occupying the preferred pool will lead to improving the performance. Notice in Figure 155 that with both approaches the percentage of time when pools #3 or #4 are allocated to link #2 is higher when spectrum mobility is considered than when it is not, which explains the significant differences in terms of dissatisfaction probability.

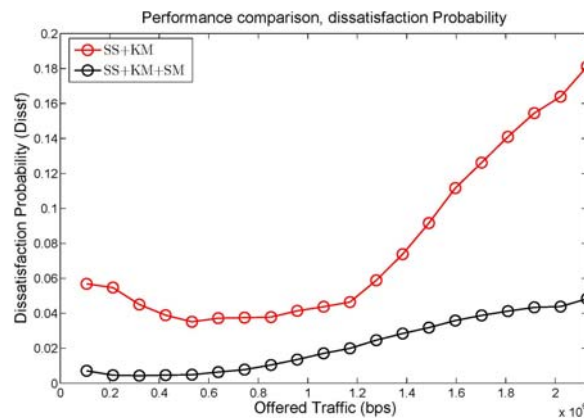


Figure 154: Effect of Spectrum Mobility in terms of dissatisfaction probability

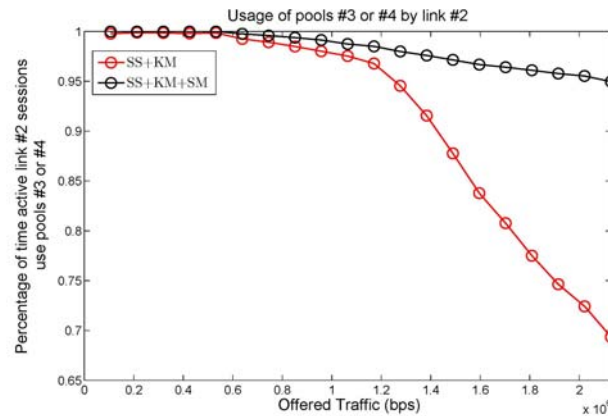


Figure 155: Effect of Spectrum Mobility in terms of usage of pools #3 or #4 by link #2

Focusing now on the strategy making use of spectrum mobility, Figure 156 presents the impact of the two different fittingness factor functions that were analyzed in section 4.2.2.1 in terms of the number of spectrum handovers per session that are required for the two considered types links. It can be observed that the selection of one or other function has a relevant influence and in particular there is a very important reduction in the number of required SpHOs for link #2 when function $f_2(U_{l,p})$ is used (at the expense of a slight increase in the SpHO required for link #1). The reason is that, as discussed in 4.2.2.1, with function 2 the decision making algorithm performs a more adequate allocation at session start. On the contrary, with function 1 it occurs more often that, at link establishment, the desired pool is already occupied and thus a SpHO will be later on needed when the link occupying this pool is released, thus increasing the SpHO rate in comparison to the use of function 1.

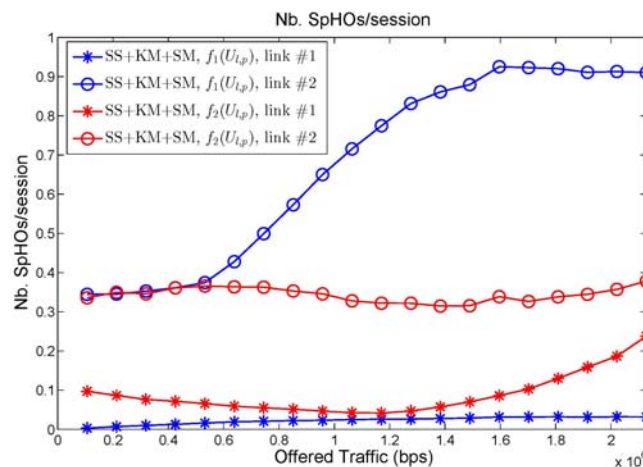


Figure 156: Influence of the fittingness factor function in terms of the number of spectrum Handovers per session

Figure 157 analyses the effect of two different criteria in the decision making process, namely the greedy approach, which tends to allocate always the spectrum pool having the highest fittingness factor, and the proactive approach proposed in section 2.4.2.5 that selects the pool that would be most likely to provide a high fittingness factor value during the whole link session. It can be observed in Figure 157 that the use of the proactive selection allows reducing the rate of spectrum handovers thanks to a better selection at link establishment. It is worth mentioning that the performance in terms of dissatisfaction probability reveals a very similar performance for both criteria, so it is not included here.

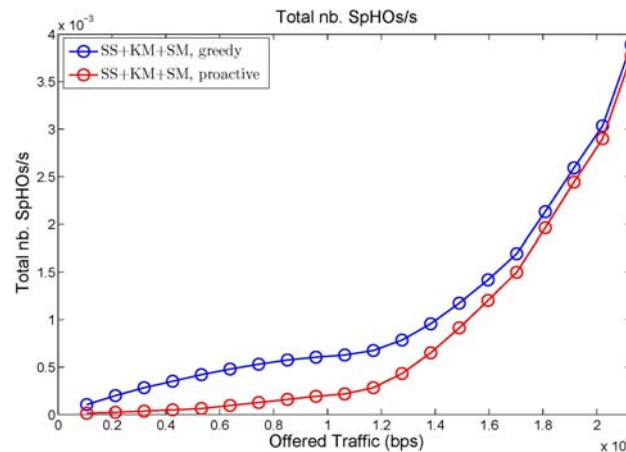


Figure 157: Influence of the decision making criterion in terms of the spectrum Handover rate

4.2.2.4.2 Adaptability provided by utility-based spectrum aggregation

Application of machine-learning (Q-learning) technique to automatically discover the optimal weights essentially removes the need for manual setting of weights. Typically in weighted sum utility formulations the weight setting is left as a manual task and as such this would require collection of data over certain periods on variations of metrics of interest and then a decision as to which metric should be associated with highest weighting (depending on analysis of historical records). The proposed approach automatically learns to set to best weights (based on learning) and associates these with the various metrics. This level adaptability is particularly useful in real operational environments.

4.2.2.4.3 Adaptability provided by fuzzy decision making

Fuzzy decision making system can be used to select among spectrum sensing methods to obtain information about spectrum availability. The developed fuzzy decision making system presented in [4] and [5] is flexible and it can adapt to changes in the operational environment as it selects the method that best fits the situation. The developed decision making system selects the spectrum sensing method between energy detection, correlation-based detection, waveform-based detection and cooperative energy detection. The selection is made based on a limited set of input parameters, i.e. the required probability of detection, operational SNR, available time, and available a priori information. The parameters are described in a way that changes in the operational environment, such as policies or propagation conditions, are reflected in the input parameters and the decision making system proposes the sensing method that best fits the given situation. Moreover, changes in the assumptions of the spectrum sensing methods can be taken into account by changing the outputs of the corresponding rules. Thus, the fuzzy decision making for the selection of spectrum sensing methods provides adaptability to the changing environment. The results will be included in D4.3.

4.2.2.5 Benefits of using utility-based spectrum aggregation

The spectrum opportunities identified by a node in the opportunistic network scenarios could be too narrow to support required bandwidths [43]. In this case, multiple spectrum opportunities can be utilized simultaneously by cognitive radios through spectrum aggregation. While the technique is expected to deal with the bandwidth extension, it can also ensure full flexibility of spectral employment over multiple bands given channel switching and complexity constraints/requirements. In the proposed spectrum aggregation and allocation scheme, the number of sub-channels and the number of bands for aggregate channels is considered as the complexity of spectrum aggregation. The proposed algorithm allocates the aggregate channel with less complexity, to nodes. At the same

time, minimizing the channel switching and maximizing the achievable throughput are aimed together. Three different objectives are integrated into a weight-sum utility function.

4.2.2.6 Benefits of the joint consideration of the RAT in the spectrum selection problem

To be able to form a link between two nodes not only the frequency for data transmission can be selected but also the RAT needs to be chosen. For instance, in TV band the used RAT in the future could be LTE, LTE-A or 802.11af. In other bands such as IMT and ISM band (2.4 GHz and 60 GHz) used RAT could be LTE and LTE-A and 802.11a and 802.15.3c respectively. In these bands the RAT capabilities and features can be seen as criteria for selecting band and RAT combination. Each RAT is able to provide a certain spectral efficiency. This spectral efficiency depends on used modulation scheme and bandwidth. Also different techniques provide different end to end latency. Intuition says that it is most favourable to select RAT offering best bit rate and lowest latency in selected band. On the other hand such phenomena like user load per access technique can be exploited in decision making and balance the load thus providing more fluent data transmission to the entire network. Since required bit rate and latency varies depending on used application, for less demanding application the use of lower data rate and higher latency RAT is adequate. For this kind of applications the selected RAT can be the technique which satisfies their bit rate requirement even though it doesn't provide the best bit rate. By doing so the less occupied RAT can be favoured leaving high bit rate low latency RATs to delay and bit rate sensitive services to meet their QoS requirements. Since the delay and achieved bit rate varies depending on user load in particular access technique in the same geographical area it is efficient to balance load between different RATs. Also operator preferences can be considered so that the use of 802.11a and 802.15.3c RAT operating in license free spectrum bands can be favoured whenever possible. This will balance the load from operators own band and base station.

In this simulation three different traffic types namely voice, streaming and web browsing are considered. The required minimum bit rates for voice, browsing and streaming users to maintain the required QoS level are 60 kbps, 13 kbps, and 384 kbps respectively [12].

We run the simulations over five TV bands which each have 8 MHz bandwidth, one 2.4 GHz band with 20 MHz bandwidth, one IMT band with 20 MHz bandwidth, and one 60 GHz band with 100 MHz bandwidth. We use modular decision flow for RAT and band selection presented in section 2.3. Objective function weights $\omega_1, \omega_2, \omega_3$ are selected between [0 1] depend on the used application. For instance, operator preferences and spectrum availability are weighted more for browsing users and throughput for voice and streaming users.

Single carrier frequency division multiplexing(SC-FDMA) is considered. For TV and IMT spectrum bands entire spectrum bandwidth is represented with subcarriers that have spectrum spacing of 15 kHz. 20 MHz band contains 100 resource blocks (RB) and each resource block is formed by 12 subcarriers and duration in time domain is 0.5 ms [13]. Since we consider uplink traffic only, reserved resource blocks for one user are assumed to be contiguous. For 2.4 GHz band we consider 802.11a where subcarrier spacing is 312.5 kHz and for 60 GHz band we consider 802.15.3c where subcarrier spacing is 1.5625 MHz. The assigned number of subcarrier and RB varies and depends on the used application and required minimum bit rate.

In this simulation, we use exponentially distributed interarrivals to model other than ON users' activity. These other users are users who don't participate ON and they can be either primary users (like in TV band) or other non-licensed users like users in 2.4 GHz band or other licensed users in the operators own band (IMT). We exploit the birth death process with death rate α and birth rate β which are uniformly distributed between 0.1 and 0.5. Expected transmission time without switching is $1/\beta$ and switching delay is 1.5 s.

Figure 158 shows RAT selection for 20 voice users, 20 browsing users, and 20 streaming users. The spots where 60 GHz band is not selected refer to situations where range between two nodes is too high and 60 GHz band is not suitable due to poor channel conditions.

As can be seen from Figure 158 browsing users with smaller capacity requirements are allocated to use 802.11a RAT thus leaving RATs capable to provide higher data rates and less delay to users demanding higher bit rates for meeting their QoS requirements like voice and streaming users. Voice and streaming users are allocated to use more often LTE and LTE-A and whenever transmission range is narrow enough all user types select 802.15.3c. This will alleviate traffic load in more popular RAT leaving more space for users who need to occupy LTE or LTE-A.

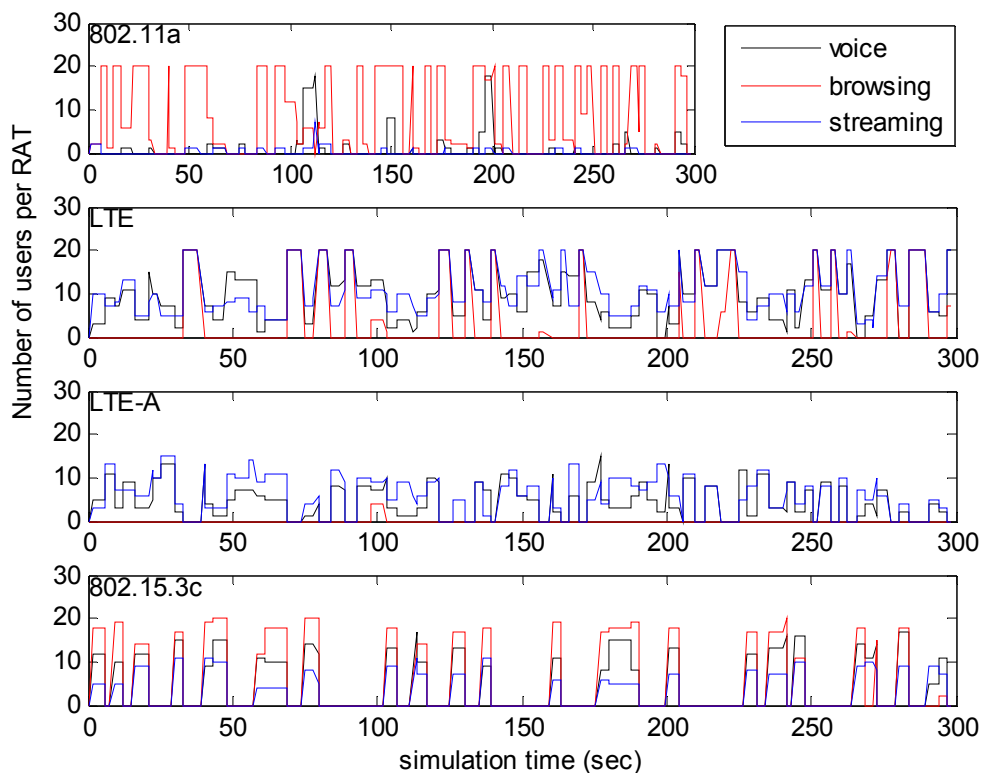


Figure 158: RAT selection for voice, streaming and browsing users

4.2.2.7 Benefits of including sensing using fuzzy logic in the spectrum opportunity identification & selection problem

After the spectrum band is selected, its availability needs to be checked using one or several methods to obtain knowledge about the spectrum availability including e.g. control channels, databases and spectrum sensing techniques. The selection among the methods depends on the regulatory requirements set for the given band. In case of spectrum sensing, a fuzzy rule-based decision making system presented in [4] and [5] can be further used to select among the sensing techniques. The performance of the fuzzy decision-making system is evaluated by assessing the proportions of the different outcomes of the decision making with different input parameter distributions. The four input parameters including the required probability of detection, operational SNR, available time, and available a priori information can get values corresponding to “low” or “high”. To evaluate the proportions of the different outcomes, we select the rules resulting in a given output from the rule base and weight the resulting rules with the probabilities of the occurrence of the rules. In addition, the success rate of the decision making is evaluated by comparing it to a situation where the decision-making is not used but a single spectrum sensing method is always used instead. The success is evaluated by evaluating the percentage of occasions where a given sensing technique is applicable with certain input parameter distributions, but may not be the best one at hand.

We have set the input parameter distributions for the four input parameters such that they all get the value “low” with a probability of 0.2 and the value “high” with a probability of 0.8. The outcomes obtained from the fuzzy decision making are shown in Table 12. The first row denotes the output from the decision making which indicates the probability that a given sensing method is selected as the method to be used. For example, 16% of the time the output from the decision making is energy detection and 51.2% it is correlation detection with the given input parameter distribution. No sensing method is applicable to the situation in 7.2% of the times. The second row presents the success rate when a single sensing method is fixed and it is used all the time instead of using the adaptive decision making system that selects the most fitting spectrum sensing method. For example, if energy detection is always used, it is successful only in 16% of the cases with the given input parameter distribution which means that 84% of the time the use of energy detection fails. Correlation detection is successful in 64% of the occasions. The results indicate that a single sensing method is not applicable in many situations which will result in system failure in many occasions. When the adaptive decision making system for the selection of the most suitable sensing method is used, we can avoid failures and only 7.2% of the time none of the sensing methods is applicable. Therefore, the selection of the most proper sensing method can be very beneficial for the system performance.

Table 12: Outcomes from fuzzy decision making for spectrum sensing selection

Sensing method	Energy detection	Correlation detection	Waveform detection	Cooperative energy detection	No sensing method applicable
Results					
Output from decision making	0.16	0.512	0.128	0.128	0.072
Given sensing method is successful	0.16	0.64	0.64	0.288	1

4.2.3 Conclusions

This chapter has presented the result of the integration and synergies identification work in terms of the technical challenge of spectrum opportunity identification and selection. A comprehensive OneFIT solution has been presented, based on the interaction between a decision making entity and a knowledge management functional block which use the information captured from the radio environment, categorized in terms of context awareness, operator policies and user/application profiles. An evaluation of the different elements of the framework has been presented to consolidate the importance of the different specificities brought by the different solutions. First, the importance of using properly defined utility functions has been stressed, by analysing different fittingness factor functions that relate with the utility perceived by the link application. Then, the benefits brought by the use of knowledge management have been illustrated by comparing a spectrum selection strategy not making use of knowledge management with a strategy using it. It has been obtained that performance in terms of dissatisfaction probability can be highly improved with the use knowledge management mechanisms. Machine learning mechanisms have also been considered, allowing the automated management of complex interactions and trade-offs between metrics without manual intervention. The benefits brought by the adaptability to the environment have also been presented, including (i) the adaptability provided by spectrum handover to deal with variations in interference in different spectrum bands and with modifications in the current allocation due to link releases, (ii) the adaptability provided by spectrum aggregation using Q-learning, and (iii) the adaptability provided by the capability to adapt the sensing mechanism by means of fuzzy logic. The specific improvements brought by the use of spectrum aggregation to assign multiple bands to the same connection, and by the joint consideration of RAT and spectrum selection have been discussed. Finally the benefits of properly choosing the spectrum sensing mechanism based on a fuzzy logic strategy have been pointed out.

4.3 Comprehensive OneFIT solution for nodes and routes selection

4.3.1 Description of the solution

Decisions regarding identification and selection of nodes and routes are conducted both locally and in a centralized manner. Locally, decisions are made within network nodes (terminals and infrastructure nodes) with help from centralized operator's management (policy acquisition, profile assignment, broader knowledge). Also, decisions can be made in a centralized management system which monitors the whole operator's network and has more processing power and broader knowledge for pervasive decision making. Framework for comprehensive solution regarding nodes and routes selection/detection is shown in Figure 159.

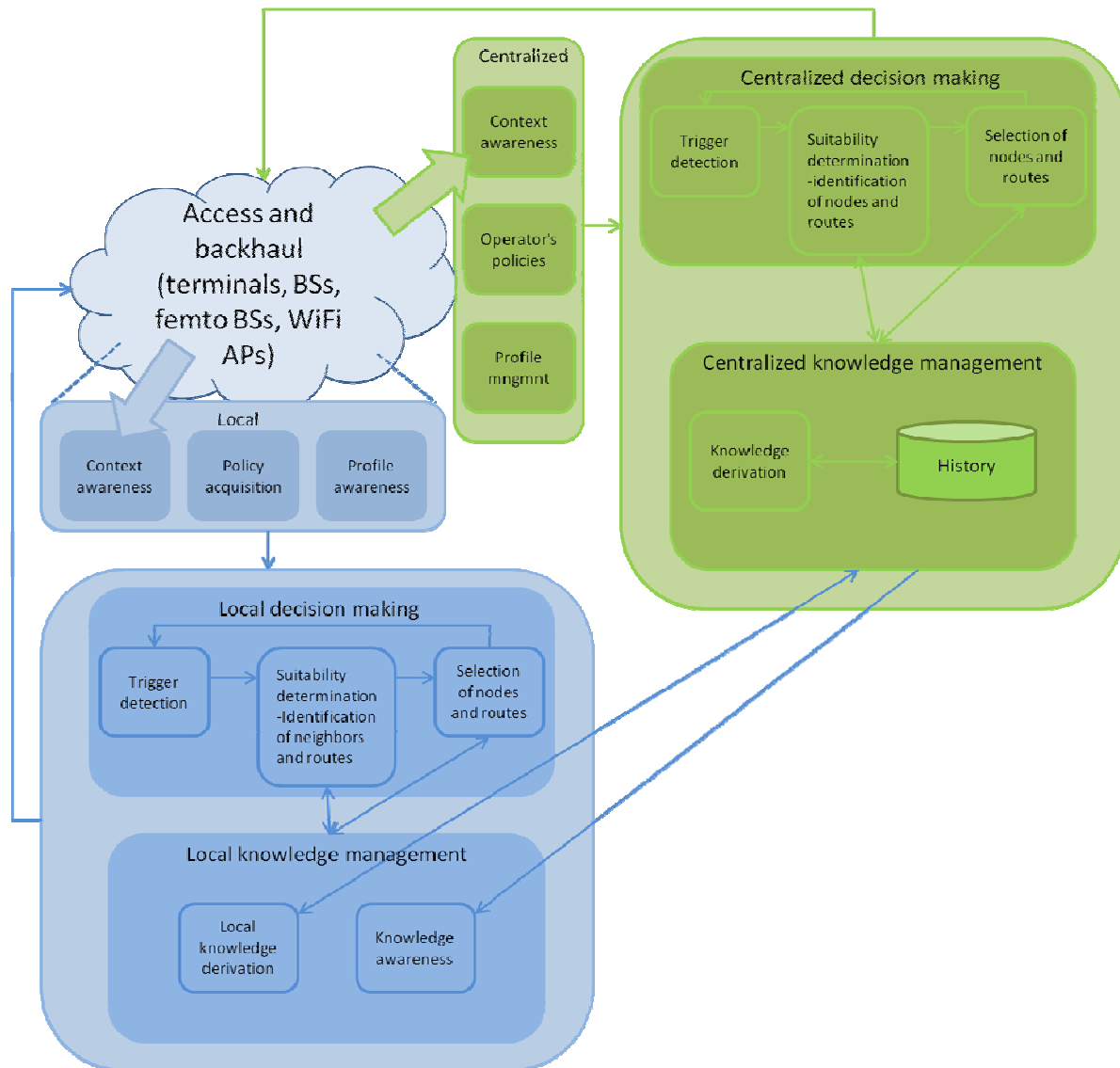


Figure 159: General framework for selection of nodes and routes

4.3.1.1 Centralized nodes and routes selection and identification

Operator's network monitoring system provides necessary context gathering/awareness which includes monitoring of the underlying network as well as monitoring of established ONs (for performance evaluation). Policies (QoS requirements, cooperation policies, power savings, power and spectrum regulations, ON related policies etc.) are defined and maintained by the operator and centralized management system has a constant access to these policies which are included in all aspects of decision making and knowledge derivation. Operator's management system is also

responsible for defining profiles of users, applications and locations (where infrastructure elements are installed) as well as connections between these profiles. WP4 algorithms provide different aspects of centralized decision making and knowledge derivation and usage. Different algorithmic approaches define different triggers which will start the suitability determination phase. The main task of suitability determination is to decide whether or not to use an ON as a solution to the detected situation. Identification of nodes and routes suitable for creation of an ON is the result of suitability determination. Previously gathered knowledge and currently detected context drive the process of selecting the nodes and routes from candidate sets. We have identified some similarities and differences in this decision making process among different algorithms. Figure 160 provides information on the complementarities of identified algorithms according to scenario and ON management stage.

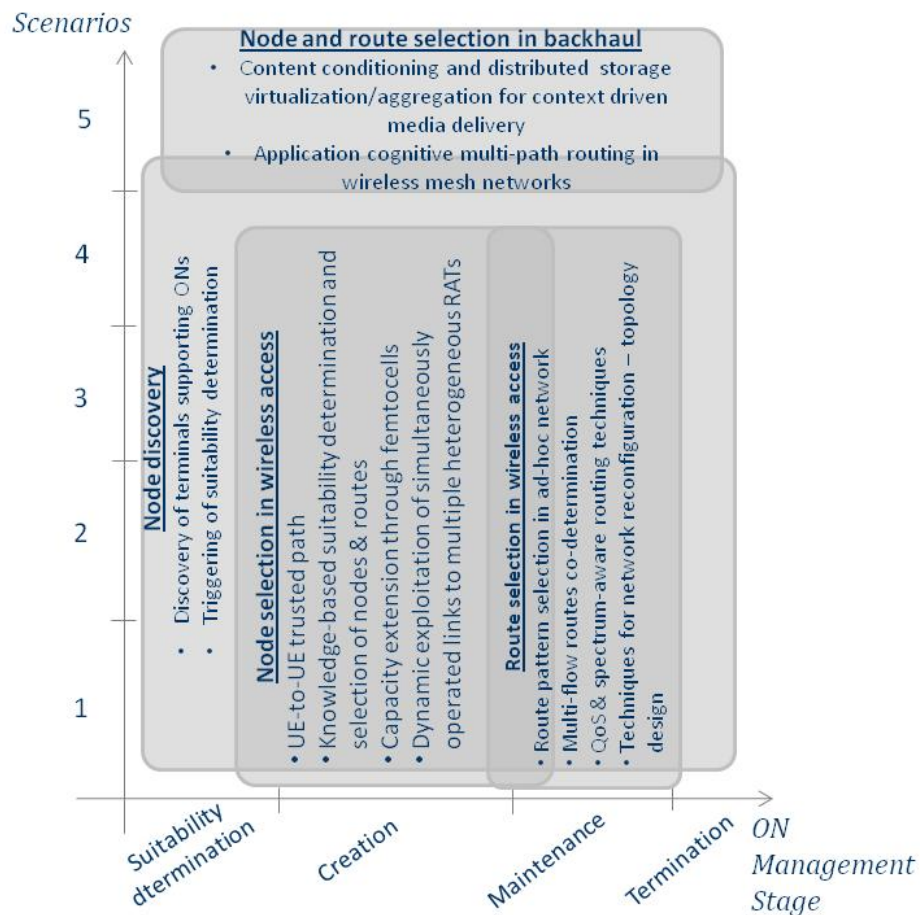


Figure 160: Complementarities of identified algorithms according to scenario and ON management stage

Centralized knowledge management includes knowledge derivation and storing. Knowledge is always derived from the current context, previously gathered context and derived knowledge. Previously derived knowledge will change as the system evolves and networks environments changes. Centralized management provides knowledge on:

- Node capabilities and status
- Network topology
- Available paths
- Performance of previously established ONs
- Users' mobility patterns
- Users' request distribution

- Traffic patterns in both access and backhaul part

When decision is made, centralized management system sends commands for performing necessary reconfigurations in order to enable creation of ONs.

4.3.1.2 Local nodes and routes identification and selection

Certain WP4 algorithms (e.g. routing algorithms) run on user terminals which enables these devices to start their own decision making process in cooperation with the centralized management system. Terminals locally monitor their environment in order to detect their neighbours and possible links/routes. They acquire policies from centralized management as well as profiles which they can assign to running applications, their neighbours, their current location and to themselves.

Locally detected triggers are mainly in line with QoS requirements dictated by the running applications (bandwidth, delay and jitter requirements) or in line with the status of the terminal (out of coverage, broken interface, low battery level etc.). Suitability determination in a terminal (or other networking nodes) checks node's capabilities, defined fittingness function values, QoS requirements and gathered context of surrounding environment. After suitability determination, neighbouring nodes and potential routes are identified. Operator's policies are inspected and appropriate set of nodes and routes is selected. Locally, networking nodes can derive knowledge about their environment (mobility of the relaying node, node's mobility pattern, available capacity, nearby infrastructure nodes, power consumption tendency etc.). In order to maintain operator's governance of all ONs, local knowledge management needs to acquire knowledge from centralized knowledge management system. Also, locally derived knowledge is reported to the centralized management system for enhancing the existing operator's knowledge database. After a decision is made, networking element performs necessary reconfiguration and coordinates with selected nodes in order to establish an ON.

4.3.2 Performance evaluation

This section intends to provide advantages of the various approaches regarding the selection of nodes and routes in order to present specific, consolidated solutions. To that respect, specific benefits have been identified in order to be able to show the importance of each metric to the ON performance. Identified benefits are summarized to distinct subsections in order to group the aforementioned algorithmic results according to their benefits.

4.3.2.1 Benefits in energy consumption of the infrastructure

This subsection analyses the benefits in energy consumption of the infrastructure which are evaluated through the various solution enforcements. Initially, the benefits in energy consumption of the infrastructure through the exploitation of small-sized cells/ femtocells are evaluated. According to this approach, specific number of femtocells is deployed in the service area of a BS. The main aim of the approach is to offload the traffic of a proportion of the terminals connected to a congested BS by redirecting them to the available femtocells, through the creation of an ON among the terminals and the femtocells. Moreover, not only rerouting of terminals to femtocells takes place according to the proposed solution, but also the allocation of the minimum possible power level to femtocells, which is required to cover the most users possible, is executed. Furthermore, the algorithm utilizes an objective function (OF) to evaluate the quality of each solution.

Aligned with these statements, Figure 161 illustrates a comparison of the energy consumption of the BS when 10, 20, 30 or no femtocells are present. The vertical axis indicates the BS total energy consumption, while the horizontal axis depicts the network type, i.e. a network without femtocells and with 10, 20 and 30 femtocells. More specifically, when 10 femtocells were enabled to the network the energy consumption of the BS decreased by 18.54%. When 20 femtocells were enabled in the network, the energy consumption of the BS was reduced by 19.72% in comparison with the case where there were no femtocells. Finally, when 30 femtocells were enabled, the energy

consumption of the BS was reduced by 20.01% percent. Therefore, as femtocells are deployed to the network, the energy consumption of the BS decreases. However, after a point where most of the traffic has been rerouted to the femtocells, the addition of more femtocells is not that much beneficial.

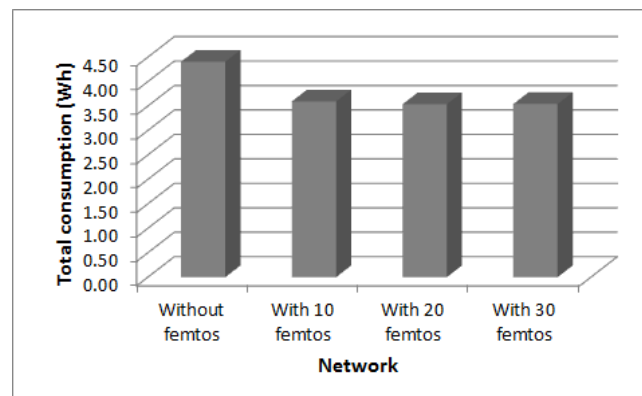


Figure 161: Energy consumption comparison for a BS with 0, 10, 20 and 30 deployed femtocells

Another aspect which impacts the energy consumption of an infrastructure element (BS) is the exploitation of neighboring terminals. In this case, terminals are able to connect to neighboring terminals in order to form an ON. According to this approach, traffic will be redirected to neighboring BSs, so the energy consumption of the congested BS (before the solution enforcement) it is expected to drop due to the offloading of terminals to neighbouring BSs. Figure 162 illustrates the average gains in the transmission power of the congested BS. The horizontal axis of Figure 162 shows the simulated time in seconds while the vertical axis provides the average transmission power of the congested BS in Watts. The figure suggests that as more terminals of the congested BS switch to ON the energy savings in the BS range from 15 to 25%.

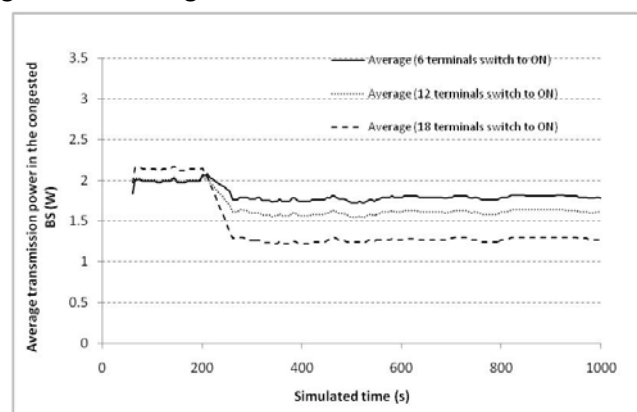


Figure 162: Average transmission power of the congested BS before and after the solution enforcement

Research [44] has shown that inclusion of the networking nodes (routers, switches and APs) into the content placement and delivery process can significantly reduce power consumption level of the content delivery networks. Since networking elements work all the time, whether or not they are included into content placement and delivery, their base power consumption cannot be considered as power consumption introduced by a CDN system. Typically, CDN systems are composed of strategically distributed dedicated content caching and delivery servers whose total power consumption (base and power consumed for CDN service) has to be included into power consumption introduced by a CDN service.

The mathematical model of the algorithm presented in section 2.13.1 derives an optimal selection of WMN nodes on which to place video content (based on status of the underlying WMN, users' request distribution and content popularity). The objective function of the mathematical model minimizes the average delivery tree length. A modified model with two optimization criteria is presented in [45]. One criterion is minimization of the delivery tree length and the other is minimization of power consumption. Results presented in the paper show that these two criteria are opposing one another in a sense that average delivery tree length minimization tends to distribute the contents as much as possible while power minimization tends to a more centralized content placement. However, results in [45] clearly show that placing the content on the WMN nodes (APs and GWs) results in up to 10 times less power consumption when compared with content delivery from a dedicated centralized server. Since WMN nodes are networking elements which are always active, only a power consumption introduced by additional storage and content delivery engine of the WMN nodes is included into the total power consumption of the CDN service. Figure 163 shows how a power consumption of a pervasive wireless CDN system drops when storage size of the WMN APs increases (unit is the average number of video files which can be placed in available WMN storage space). This result is a direct cause of tendency of the power consumption optimization criteria to involve fewer nodes into the content delivery service.

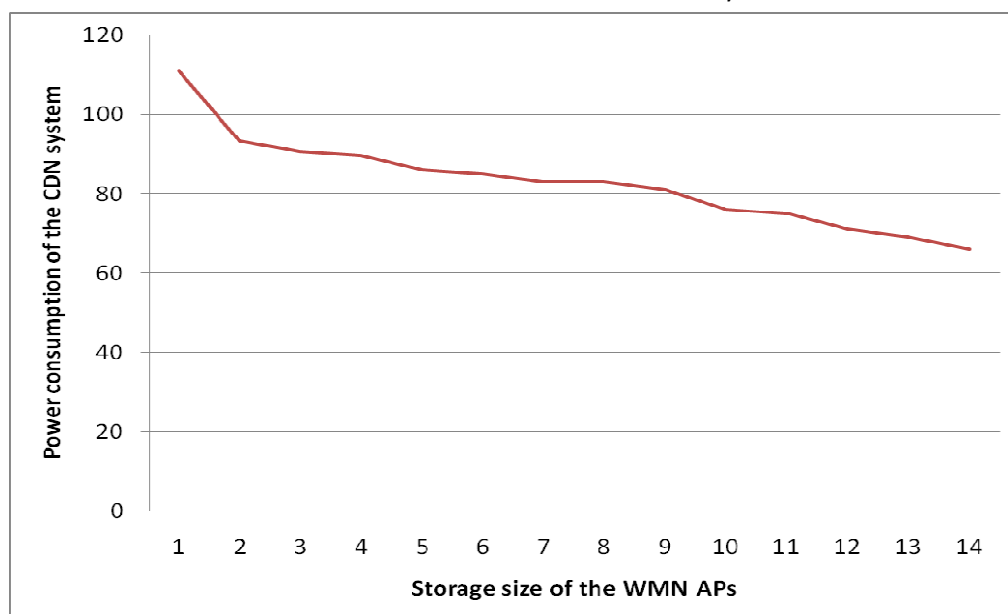


Figure 163: Power consumption of a WMN CDN system as a function of a storage size on APs

4.3.2.2 Benefits in energy consumption of the terminals

Following the previous identification of benefits, this subsection analyses the benefits in energy consumption from the scope of the terminals this time. As previously, the benefits in energy consumption of the terminals are evaluated through the exploitation of small-sized cells/ femtocells. According to this approach, Figure 164 depicts the progress of the energy level of a macro UE (i.e., terminal connected continuously to a BS) versus the progress of the energy level of a femto UE (i.e., a terminal connected continuously to a femtocell) and versus the progress of the energy level of a UE (i.e., a terminal which switches from BS to femtocell and vice-versa). It is assumed that the energy of a terminal decreases as time progresses and that also decreases when data are transmitted. In addition, it is assumed that the terminals send data every 30 secs. Apparently, the energy of the femto UE decreases at a lower rate since the terminal needs less transmission power to communicate with the femtocell, while the energy of the macro UE decreases in a higher rate due to the needed high transmission power. On the other hand, the progress of the energy level of the UE is in the middle of the progress of the femto-UE and the macro-UE as it was expected since when

it is within the coverage of an available femtocell, it connects to the femtocell, otherwise it connects to the BS.

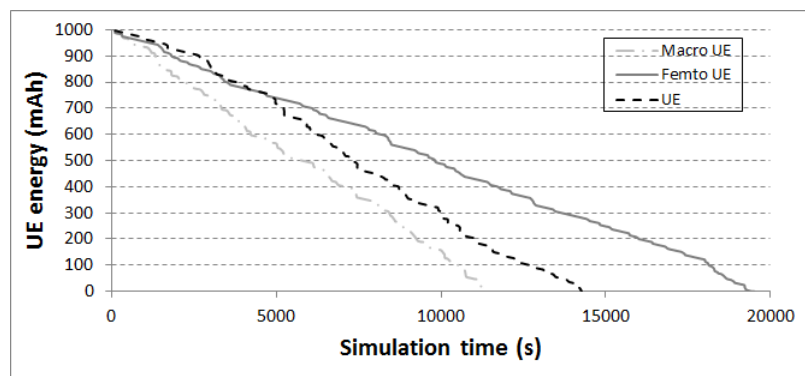


Figure 164: Progress of the energy level of macro-terminals, femto-terminals and terminals that connect both to macro BSs and femtocells

Moreover, in the figure that follows, an ON is created through the connection of neighbouring terminals in order to redirect traffic from a congested BS, to a non-congested neighbouring BS. Framed in this statement, Figure 165 provides a graphical representation of the average transmission power of terminals that switch to ON in each test case as presented in section 3.8. The horizontal axis of the figure enumerates the test cases while the vertical axis provides the average transmission power of terminals that switch to ON. A decrease of the metric is observed which ranges from 10 to 50% depending on the test case. Also, the decrease is greater in the cases where 6 terminals switch to ON, since these terminals tend to be nearer the edges of the cell, hence transmission power is greater before the solution. On the other hand, when 12 and 18 terminals switch to ON, there is a greater variety of distances of terminals from the centre of the cell, so the decrease in energy savings is lower.

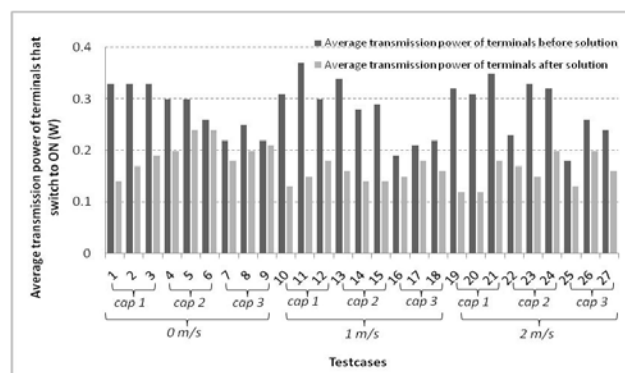


Figure 165: Average transmission power of terminals that switch to ON in each test case

4.3.2.3 Communication benefits in terms of load and delay through the exploitation of ONs

Another identified benefit through the proposed solutions on selection of nodes and routes are the benefits related to communication in terms of load and delay through the exploitation of ONs. Specifically, Figure 166(a) illustrates the progress of the normalized load of the macro BS before and after the solution. The normalized load corresponds to the sum of the load of the terminals divided by the capacity of the BS. The trend of the load is to decrease as soon as the solution is enforced, while the femtocells which acquire a proportion of the traffic from the congested BS are expected to experience a slight increase in their load as Figure 166(b) suggests.

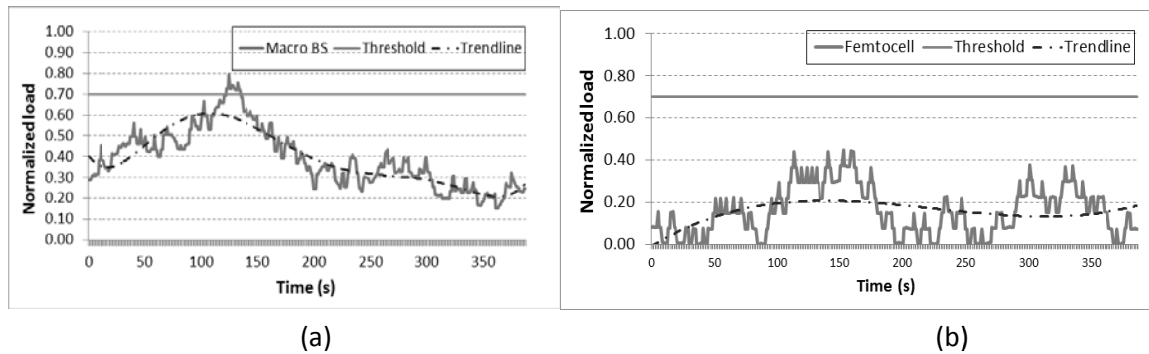


Figure 166: Normalized load of (a) the macro BS and (b) a femtocell before and after the offloading to femtocells

Furthermore, Figure 167 provides the average delay for delivering messages from all 40 terminals in the congested BS after the solution, for each one of the 27 investigated cases as described in section 3.8. This is also compared to the average delay in the congested BS, before the solution enforcement. As delay, is considered the difference between the creation time of a message till the successful delivery of the full message to the final destination (which is always a BS). The horizontal axis shows the testcases and the vertical axis provides the average delay in seconds. In all cases, the proposed scheme seems to perform better compared to the congestion situation. The decrease in the delay is higher (around 35%) when 18 terminals switch to ON and decreases to around 25% and 15% when 12 and 6 switch to ON respectively.

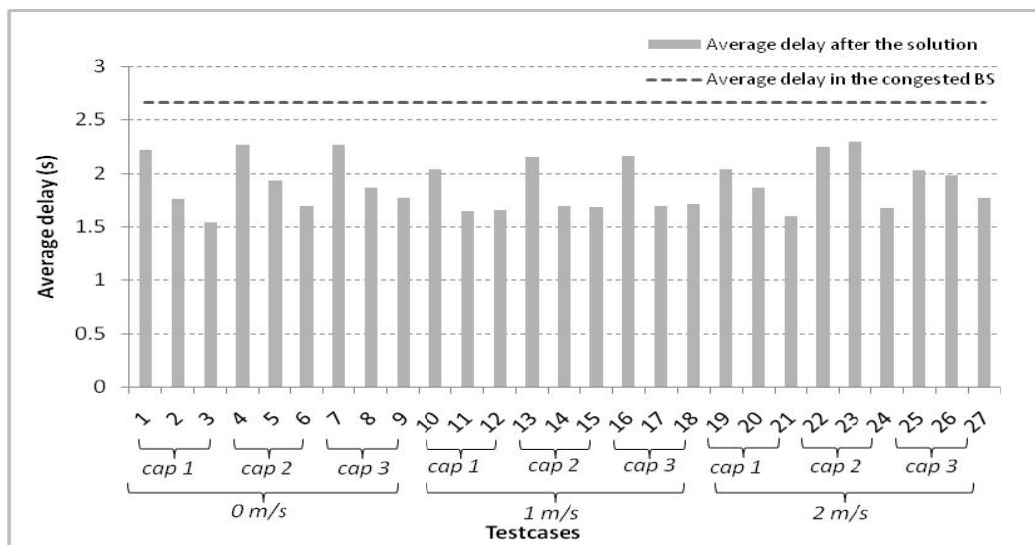


Figure 167: Average delay measurements for the transmission of a whole message (64KB-1024KB) in each testcase

In content delivery services, placing content closer to the requesting users decreases the delivery tree length and, consequently, decreases delay and jitter. Mathematical model introduced in section 2.13.1 selects the optimal set of nodes among candidate nodes on which to place a video content. The optimality is achieved with respect to the average delivery tree minimization criterion while taking into account status of the underlying WMN, APs' storage capacity and status and users' request distribution. Figure 168 shows how the ADTL value decreases (and with it delay and jitter) as the number of WMN nodes, which are selected for optimal content placement, increases.

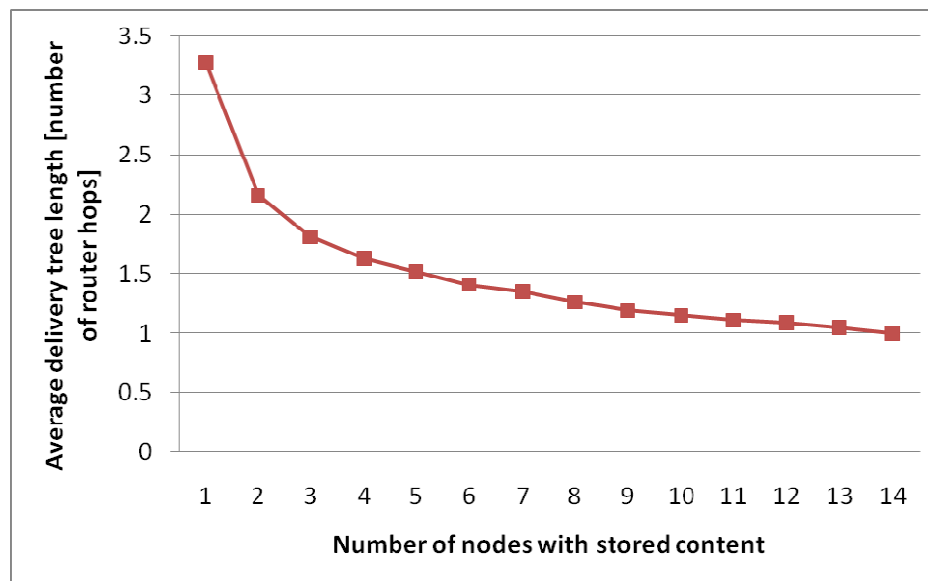


Figure 168: ADTL as function of the total number of WMN APs selected for content placement

4.3.2.4 Resource utilization benefits in terms of increased capacity of the underlying network

Nodes and routes for creating the ON can be selected with the goal to increase the resource utilization in underlying networks. For example, placing content on WMN nodes increases the delivery capacity of the WMN with respect to the stored content. If the stored content is a very popular video, which is requested by many local users, then the increase in WMN's delivery capacity becomes more significant. Algorithm proposed in section 2.13.1 provides optimal selection of WMN nodes, on which to place video content, with respect to users' request distribution and content popularity. According to [21], placing a video content on WMN nodes, which have the ability to address each other's cache misses, results in the same increase of the WMN's content delivery capacity as introduction of new GWs into the WMN constellation. A more detailed analysis of this effect can be found in section 3.15.2, while Figure 169 provides the results related to the total video streaming capacity of the WMN (with respect to particular content) which is expected to increase with the number of WMN nodes with stored video content.

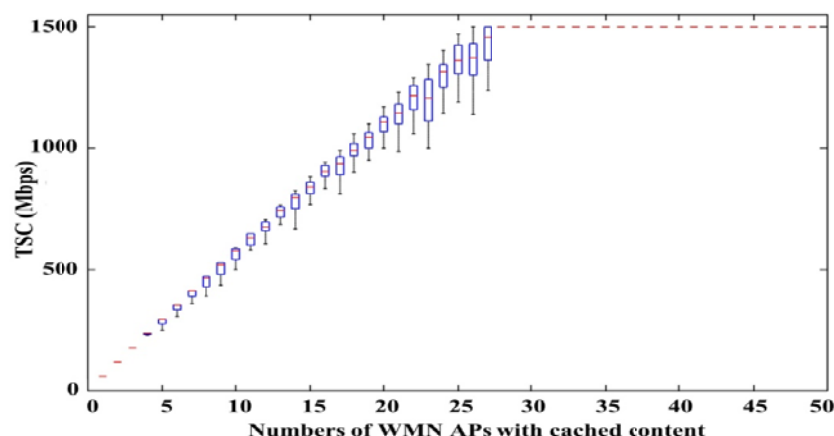


Figure 169: Total video streaming capacity of the WMN (with respect to particular content) increases with the number of WMN nodes with stored video content

Multipath routing algorithm described in section 2.12 provides load balancing in the backhaul side of the WMNs. Detailed analysis regarding performance of this algorithmic approach can be found in

section 3.13.2. Backhaul bandwidth aggregation can be combined with algorithms which work in access side of wireless networks in order to achieve overall load balancing and bandwidth aggregation. This cooperation of the algorithms can provide the highest level of bandwidth resource utilization and near theoretical capacity of the underlying wireless network (i.e. WMN). Figure 170 depicts the average available bandwidth on access side of a WMN AP which increases if application aware multipath routing is established.

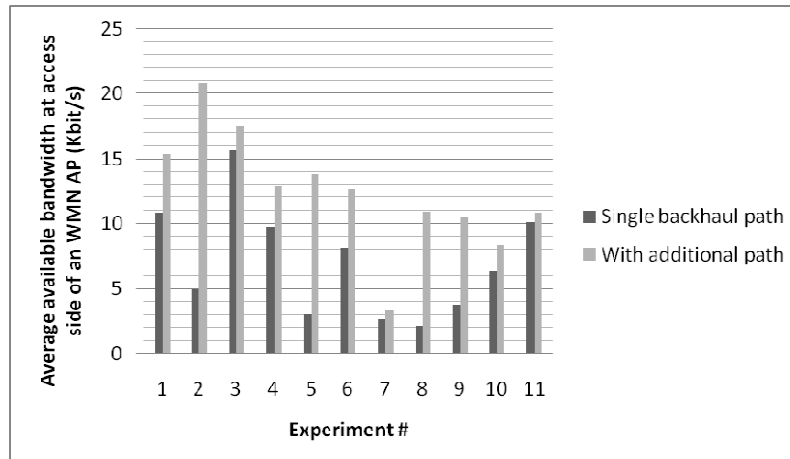


Figure 170: Average available bandwidth on access side of a WMN AP increases if application aware multipath routing is established

4.3.3 Conclusions

This section provided information on the synergies related to the research domain of nodes and routes selection in the wireless access and in backhaul segments. Definition of synergies between various algorithmic approaches of partners has led to the identification of complementarities and specificities of each proposed solution. To that respect, specific benefits have also been analyzed according to the experimental results of each solution. Benefits have focused mainly on the areas of energy consumption of the infrastructure, energy consumption of the terminals, communication benefits in terms of load and delay through the exploitation of ONs and resource utilization benefits in terms of increased capacity of the underlying network. The analysis of these benefits is also supported by indicative results that derive from the synergic exploitation of various solutions. Specifically, it is proven that in terms of energy consumption in the infrastructure, infrastructure elements are benefited from the creation of ONs as fewer nodes may be directly connected to an already congested BS which leads to lower energy consumption of the BS. Studies and experimental results have shown that placing a content on carefully selected subset of infrastructure access nodes (APs, BSs) can reduce energy consumption of content delivery services (traffic is offloaded from dedicated servers). Also, terminals which switch to ON shall experience less power consumption rather than trying to communicate directly to a distant, congested BS. Studies also on the ON nodes that act as intermediate nodes (thus acquiring some extra traffic), have shown that the increase in their consumption is not so radical and is also limited if the intermediate nodes are moving. On the other hand, as mobility level increases, the loss of messages shall rise and also an impact on delay may be experienced. Finally, regarding the resource utilization benefits in terms of increased capacity of the underlying network it is suggested that the placing of content on WMN nodes increases the delivery capacity of the WMN with respect to the stored content. If the stored content is a very popular video, which is requested by many local users, then the increase in WMN's delivery capacity would become more significant. Also, multipath routing in ad-hoc networks (mobile and stationary) will provide better load balancing and higher level of available bandwidth utilization, thus increasing achievable communication capacity while avoiding well known multipath routing issues (i.e. jitter, packet reordering).

5. Conclusions

This deliverable has presented and evaluated the algorithmic solutions for enabling the management of opportunistic networks developed in the OneFIT project. Each algorithm has been specified, pointing out its integration with the OneFIT architecture and with the C4MS signalling, and it has been evaluated according to proper KPIs in representative scenarios, including also aspects related to the practicality of the proposed solutions proposed. In the following, a list of the major conclusions that have been obtained from the evaluation of each algorithm is provided.

- Suitability determination: This document has addressed first the ON suitability determination algorithm, focusing on the “infrastructure supported device-to-device communication” and “coverage extension” scenarios. Two algorithms have been proposed and have been evaluated. The following conclusions have been obtained:
 - In the case of the direct D2D communication it has been obtained that the probability for direct connectivity largely depends on the probability of the users being in the same “Area of Interest” (AOI) and if the range of the wireless interface is around the size of the AOI or larger. Further on an ON can be maintained for a long time if the users are not moving but the possible lifetime of an ON decreases with the velocity of the users. Such infrastructure supported device-to-device communication is mainly attractive in places with many users and local communication needs (e.g. in a household, on a campus, an office building, during a sports event or a group of people being on travel), whenever other local hot spot access points do not exist or do not provide a sufficient QoS to offload traffic.
 - Another important scenario for opportunistic networking is the case where a user can not directly access the infrastructure because of being out of the direct coverage or because of not supporting the radio access technology provided by the network. The solution in this case is to establish an opportunistic network with a so called “supporting device” in the neighbourhood which then relays the traffic to the infrastructure. This document has presented the probability of finding such a supporting device in dependency of the range of the direct interface and in dependency of the supporting device density.
- Spectrum opportunity identification and selection: One of the relevant technical challenges in the ON formation is the decision on which spectrum has to be assigned to the different links existing in an ON. In this context, this deliverable has considered the following approaches:
 - Modular decision flow approach for selecting frequency, bandwidth and radio access technique for ONs: The proposed decision flow selects band and RAT for one or several ON links and ensures fare operation for whole ON and adequate quality of service for each user. The algorithm is employed when a new link needs to be established in the creation or maintenance phase or when a new spectrum band and RAT needs to be selected in the maintenance phase. The results show that for less data rate demanding applications such as web browsing 2.4 GHz band and 802.11a RAT are selected more often. Results also demonstrate that as the transmission range increases the selected band is IMT and RAT LTE or LTE-A for guaranteeing proper QoS for ON users.
 - Fittingness factor-based spectrum selection: The fittingness factor concept has been proposed as a novel metric that captures the time-varying suitability of available spectrum resources to different applications supported in each ON link. This metric is used in the spectrum selection and spectrum mobility algorithms executed at a decision-making entity at ON creation and ON maintenance stages, respectively.

They are supported by a Knowledge Management mechanism that involves a set of advanced statistics capturing the influence of the dynamic radio environment on the fittingness factor stored in a Knowledge Database. The performance evaluation results have shown that the proposed strategy efficiently exploits the knowledge management support and the spectrum mobility functionality to introduce significant gains (ranging from 85% to 100%) with respect to a random selection and to perform very closely to the upper-bound optimal scheme. The strategy has been evaluated from the perspective of its practicality in terms of the rate of required spectrum handovers, revealing a low rate of handovers particularly for low and medium loads, and from the perspective of the measurements exchange to support the context acquisition.

- Machine Learning based Knowledge Acquisition on Spectrum Usage: This work has proposed a novel distributed available channel identification algorithm based on machine learning, targeted at modelling the spectrum occupancy and identification of spectrum pools for opportunistic access by secondary network. The secondary nodes do not need any information from the primary system or any neighbouring nodes. Simulation results reveal that the algorithm learns by means of successful interactions with the environment (rather than relying on spectrum usage history) which resources to be used in order to avoid/not cause harmful interference as well as providing a suitable quality of service (QoS). Such intelligent schemes can provide a practical solution to the main challenge of interference in multi layer networks.
- Techniques for Aggregation of Available Spectrum Bands/Fragments: This work has considered the spectrum selection with spectrum aggregation capabilities. When it is difficult to support enough bandwidth with contiguous available spectrum, multiple small spectrum fragments (sub-channels) can be exploited to yield a (virtual) single channel by spectrum aggregation. In the proposed algorithm, total throughput, the number of channel switching, and the number of bands for aggregate channels have been considered as the performance metrics with respect to the nature of secondary user's spectrum use and aggregation capability. The utility function for three performances is developed as a weighted sum utility function. A Q-learning approach is used to determine the optimal weights. The proposed approach is shown to be adaptable to changes amongst different objectives of interest. The proposed framework included a learning module allowing for to management of complex interactions and trade-offs between different metrics without manual intervention.
- As a result of the integration and synergies identification work between the previous approaches, a comprehensive OneFIT solution for spectrum opportunity identification and selection has been presented. It is based on the interaction between a decision making entity and a knowledge management functional block which use the information captured from the radio environment, categorized in terms of context awareness, operator policies and user/application profiles. An evaluation of the different elements of the framework has been presented to consolidate the importance of the different specificities brought by the different solutions. Specifically, the importance of using properly defined utility functions has been stressed, together with the benefits brought by the use of knowledge management and machine learning mechanisms. The benefits brought by the adaptability to the environment have also been presented, including the capability to adapt the sensing mechanism by means of fuzzy logic.

- Node and route selection: Another important technical challenge in the ON formation is the capability to select the adequate nodes to form the ON and the most suitable routes between them. This technical challenge has been addressed in this document by different works:
 - Algorithm on knowledge-based suitability determination and selection of nodes and routes: This work has considered two main approaches for the ON creation. In the capacity extension scenario the proposed solution for route selection, based on the Ford-Fulkerson maximum flow algorithm, is triggered whenever a congestion situation occurs in the infrastructure and makes decisions on the establishment of routes which will redirect traffic from the congested service area into non-congested ones, assuming that each terminal in the congested service area creates one application flow which can be redirected through neighboring terminals. In turn, the node selection process during the ON creation is based on a fitness function which is a weighted, linear formula which takes into consideration different parameters of the candidate nodes. The obtained results indicate that terminals which act as intermediate nodes may experience an increase in their transmission power of 19% in average, compared to the situation when the solution is not applied, and it can range from 8 to 50%, depending on the test case. At the same time, the terminals that switch from the congested BS to an ON may experience a decrease of their consumption of 27% in average and it ranges from 10 to 50% depending again on the test case. Similarly, a reduction of 15-25% in the transmission power of the congested BS is observed. Also, the quality of communication is benefited, as delay of successfully delivered messages drops approximately 15-35%, compared to the congested situation, depending on the test case. Furthermore, an average decrease of 15-40% has been achieved in the load of the congested BSs, depending on the number of terminals which switched to ON. Finally, extra traffic related to signaling for the establishment of ONs is limited due to the limited size of the ON which means that a small number of terminals need to exchange constantly control messages.
 - Route pattern selection in ad-hoc networks: This work has proposed an algorithm for routing packets taking into account the constraints associated to the different user application classes and to control and signalling information including C4MS messages. Qualitative evaluations of the algorithm have revealed the ability of the algorithm to satisfy the end user QoE.
 - Multi-flow routes co-determination: This work has presented a first proposal of network coding optimization on multi-flow route co-determination. Optimization on this initial algorithm follows to extend the set of topologies on which the multi-flow route co-determination is applicable, with the introduction of delegated nodes. Results on an implementation of these optimizations have been presented. They show good improvements on the throughputs in terms of number of data packets to be exchanged between pair nodes, thanks to the integration of the delegated nodes.
 - QoS and spectrum-aware routing techniques: This work has proposed a routing protocol that makes an opportunistic use of the available channels in the routing process. Proposed protocol is a spectrum-aware version of OLSR routing.
 - Techniques for Network Reconfiguration – topology Design: This work has addressed the creation and maintenance of network topology through enabling coordination in decision making among the nodes taking into account different parameters to establish links/topology with a set of desired global properties and constraints (K connectivity, interference minimization and energy efficiency). Initial results indicate

that the proposed models can provide practical yet optimal power levels to minimize the power utilization while maintaining K connectivity.

- Application cognitive multi-path routing in wireless mesh networks: An algorithm has been proposed to select and establish the appropriate set of multiple paths in the wireless backhaul side of a wireless mesh network. By using multiple paths, we can achieve better utilization of the available backhaul resources and increase the overall capacity of a given WMN. Aggregated backhaul bandwidth, made available to a particular AP, can increase access capacity of that AP several times when compared to the capacity achieved through the best available single path. Compared to legacy multipath approaches, the proposed algorithm provides the same level of backhaul bandwidth aggregation with drastically increased QoS levels. Results of experiments conducted in the open platform WMN test-bed show that jitter levels tend to be lower and more stable in comparison with single path routing.
- UE-to-UE trusted direct path: In this work the problem addressed is the establishment of a WLAN network between different devices using the connections allowed by another technology. More specifically, it deals with the selection of the candidate AP and the operating channel to fulfil the QoS and power minimization requirements for all the WLAN members.
- Content conditioning and distributed storage virtualization/aggregation for context driven media delivery: This work has addressed specifically the scenario 5 “Opportunistic resource aggregation in the backhaul network” and in particular the aggregation of backhaul storage resources in wireless mesh networks. An algorithm is proposed that, based on contextual data gathered from the environment and end users, performs the node selection for multimedia content placement and distribution. Criteria for node selection is based on request distribution, popularity of multimedia content, status of caching storage of WMN nodes and user’s behaviour. The evaluation of the proposed algorithm has revealed the advantage of cache-p2p organization of WMN CDN, the robustness of the proposed MILP model with respect to different user mobility models, and that the content provider can save costs with the same QoS. Using smart caching/content placement algorithms, observed features can be further improved (for an example, if local groups of nearby APs contain complementary content, whose union is almost (or to some extent) the copy of source server’s content). Shown results are collected from “regular” scenarios, but using the presented MILP model one can examine different experimental setups, modelling and detecting “corner cases” and irregular situations in (parts of) WMN CDN.
- As a result of the integration and synergies identification work between the previous approaches, a comprehensive OneFIT solution for nodes and routes selection has been presented. In this solution, decisions regarding identification and selection of nodes and routes are conducted both locally and in a centralized manner. Centralized knowledge management includes knowledge derivation and storing including different aspects such as node capabilities, network topology, available paths, etc. In turn, some WP4 algorithms run on user terminals locally, which enables these devices to carry out their own decision making process in cooperation with the centralized management system. Performance evaluation of this approach has presented the benefits brought in terms of energy consumption in both the infrastructure and the terminals, as well as in terms of load, delay and resource utilization.

- **Capacity Extension through Femto-cells:** This work has considered the capacity extension of the congested infrastructure by exploiting nearby femtocells. In particular, it has addressed the complex optimization problem of allocation of network resources to reroute macro-terminals to the femtocells and also to allocate the minimum possible power level to these femtocells. The problem is mathematically formulated and solved by means of a novel greedy algorithm denoted as DRA (Dynamic Resource Allocation). Results from testing the proposed algorithm reveal that the proposed algorithm outperforms both Simulated Annealing (SA) and Tabu Search (TS) reference algorithms in terms of solution quality (DRA computed a solution that was 4.68% better than the one of the SA and 2.27% better than the one of the TS) and runtime (DRA algorithm proved to be 36.68% faster than the SA and 2117.10% faster than the TS). In addition, the benefits that derived from the use of femtocells at the energy consumption of a macro BS and the battery lifetime of terminals through 3 indicative test cases were studied. Simulation results depicted that the BS energy consumption is decreasing while the number of femtocells increases. Moreover, it was illustrated that the BS energy consumption increases while the number of terminals increases in the network. Furthermore, the battery lifetime of a macro-terminal, a femto-terminal and a moving terminal was studied, obtaining that the battery lifetime of a femto-terminal is significantly higher than the one of the macro-terminal.
- **Support activity to validate ON algorithms on an offloading-oriented real-deployment testbed:** This work has described the implementation of the evaluation platform that will be used to assess the performance of a macro-to-femto offloading mechanism in urban areas. First tests on the platform show indicate that the offloading mechanism behaves properly, leading to a scenario with a 70% reduction in the disconnection rate, a 35% increase in the total capacity and a 10% enhancement in the load balance indicator.

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